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WEATHER

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by Philip D. Thompson, Robert O'Brien
and the Editors of TIME-LIFE BOOKS

CONSULTING EDITORS
René Dubos
Henry Margenau
C. P. Snow

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ABOUT THIS BOOK

SCIENTISTS in all fields agree that meteorology focuses upon the biggest, toughest and probably most exciting single subject of modern scientific inquiry: the more than four thousand million cubic miles of atmosphere whose turbulent movements make the world's varied weather. This book traces the basic circulation of heat and winds from equator to poles, and explains the many phenomena of weather, from hailstones to hurricanes. It describes how modern meteorologists, armed with such tools as radar, laser beams and computers, may change civilization itself as they make more accurate predictions and possibly modify the weather.

Each chapter of text is followed by a supplementary picture essay, although each may be read independently. For example, Chapter 7, "The Inexact Art of Forecasting", which describes the operations of the U.S. Weather Bureau, precedes a picture essay on "The Home Weatherman".

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PREFACE

ANYONE WHO READS THE PAGES THAT FOLLOW can scarcely miss the air of excitement, the joy of discovery and the conviction of accomplishment that permeate the field of meteorology today. For several reasons, it is timely that the window behind which the atmospheric scientist and the professional meteorologist labour so assiduously be opened to the public view.

First, since all people suffer from the weather, benefit from the weather and support atmospheric research and weather forecasting, they have a right to know what it is all about. The meteorologist has a responsibility to tell them—as clearly and simply as it is done here.

Second, despite air-conditioned homes, automobiles and baseball stadiums, a growing population and an increasingly complex civilization are going to become more—not less—dependent on the vagaries of the ubiquitous atmosphere.

Third, advances in the pure science through which knowledge of the atmosphere is acquired, and progress in the applied science involving the use of that knowledge, are both taking place at such breathtaking speed that meteorology will be almost unrecognizable as we enter the 21st century—when half of us can still expect to be alive. The guideposts Messrs. Thompson and O'Brien have set forth will help to make the adventuresome journey a fruitful one.

Fourth, while we are no closer to meaningful control of the weather than we were in the 1940's, the problem has subtly but perceptibly been transformed from the speculative phase to one that permits the rational and systematic exploration of possibilities and limitations. The implications of this development will require no further elaboration than that found in Chapter 8.

Finally, in a world shrunk by modern communication and transportation, beset with conflict and struggling with awesome decisions involving all mankind, there is an unparalleled opportunity to develop and perfect new patterns of international co-operation in the study and the use of an atmosphere that recognizes no national boundaries.

Weather is simply too important to be left to the meteorologists. It is a delight to invite you to share in its study, understanding and use.

—THOMAS F. MALONE

Chairman, Committee on Atmospheric Sciences

National Academy of Sciences – National Research Council, U.S.A.

1

The Ingredients of Weather

TWO INESCAPABLE AND OFTEN EXASPERATING FACTS mark man's personal relations with the weather—with the state of the atmosphere as it was yesterday, as it is today, as it is likely to be tomorrow and in the near future.

One is that from his first breath to his last, it is always there. He may love it or hate it, revile it or resign himself to it; the one thing he cannot do is ignore it. Every morning there it is outside the window—raining or snowing, clear or cloudy, warm or cold. A bright, sparkling, autumn day of crisp air, blue skies, clear sunshine? He feels invigorated, stands straighter, strides more optimistically into his day. A sweltering summer morning? He feels irritable, depressed, exhausted before the day's work has hardly begun. Before he reaches the breakfast table, the weather colours and conditions man's physical well-being, the state of his emotions, his attitude towards life. Each day he takes it into account. Each day he lives by its grace, on its terms.

The other absolute is change. Whatever the state of the weather here and now, the one certainty is that it will not remain that way. Moreover, when it changes it will do so without even token reference to the needs or wishes of the humans in its path. As a heedless elephant scatters an ant-hill, so a developing storm destined to paralyse Northern Europe next week will, *en route*, totally disrupt the lives of millions of people, playing havoc with their picnics and outings, their travel and holidays, their arrivals and departures, their harvestings and home-comings. But, just as impersonally and with the same tantalizing caprice, it may come like a blessing, bringing unseasonable warmth amid the cold, refreshing sea breezes during the steaming days of summer, providing rain for thirsty lawns and crops, snow to ski on, fair winds for sailing, blue skies for flying.

The impact of weather strikes deeper than this.

A night fog drifts down over a busy main road, and a cautious driver slows down. A big lorry roaring through the mist hits him in the rear; other vehicles, unable to stop, pile into the wreckage. Toll: many dead, more injured. A freak March storm forms off Cape Hatteras, travels up the Atlantic Coast, veers towards Newfoundland, stalls, sweeps its gale-force winds back across the Eastern Seaboard, then moves on once more to decay somewhere in the North Atlantic. Stunned residents count their losses: scores dead, thousands of homes and buildings destroyed, miles of beaches washed out to sea—damage estimated in the millions. A typhoon forms near Guam, spins across the Pacific, strikes first the Philippines, then Japan, and blows away to the north-east, leaving in its wake incalculable destruction and thousands dead. A sudden cold spell hits Florida—and half the state's citrus crop, mainstay of its agricultural economy, is frost-bitten and rendered worthless. West of the Appala-

THE DAILY GENESIS OF WEATHER
This sunrise over Sleeping Bear Dunes in Michigan marks the beginning of the daily cycle of weather. While heat from the sun evaporates dew from gardens and lawns in Michigan, its energy is also driving the machinery of weather all over the world, soaking the tropics with rain, blanketing the Alps with snow—and perhaps generating a 200-m p.h. storm off Cape Horn.

chians, it rains too hard and too long, and the river Ohio goes on a rampage; east of the Appalachians, it does not rain enough, and some 11 million people living in the New York metropolitan area have their water supplies rationed.

But all this may bring its own benefits. To cope with the vagaries of the weather, millions of Americans manufacture snow tyres and bikinis, furnaces and rain-coats, sun-suits and air conditioners: they make golf clubs and patio furniture, run summer resorts in the Catskills and ski resorts in Colorado. Weather in its more benign form is the reason why one-tenth of the American nation lives in California, why the south-west desert country is booming, why the multi-billion-dollar space industry is springing up along the balmy Gulf Coast crescent.

The folk art of forecasting

Outdoor people have always had a special stake in tomorrow's weather. As a result, for thousands of years forecasting was a folk art practised primarily by sailors, farmers, hunters, fishermen. They studied the clouds, felt the air's dampness on their cheek, noted a shift in the wind, added a certain tingling in their shoulder, an ache in the left femur, checked it with the behaviour of cattle or birds, remembered pertinent sayings of their grandfathers, referred finally to their own experience and personal weather lore—and came up with an intelligent guess.

Though these methods were often amazingly accurate, weather has long since ceased to be a matter for chimney-corner experts. Today forecasting is a science called meteorology (from the Greek *meteoros*, high in the air, and *logos*, discourse). Government spending on atmospheric research in the United States reached $170 million (£60 million) in 1963, and climbs higher every year.

Thanks to electronics and the space age, meteorologists now command the instruments and machines of an exciting technology that has discovered more about weather in the last 20 years than in all previous history.

Today a satellite with a television eye spies on hurricane clouds from above, and tells meteorologists how fast and in what direction they are moving. Balloons, tracked from the ground, reconnoitre the swift-flowing wind streams of the upper atmosphere. Rockets bore through the airless reaches of outer space with radiation-measuring devices that send their data streaming earthwards in telemetered radio signals. On earth itself, electronic computers that can perform a million calculations a second assimilate information from hundreds of observation points all over the earth, sorting it, sifting it, following the instructions contained in intricate equations—and printing out, finally, the probable pattern of the upper atmosphere of the entire Northern Hemisphere for a complete 24-

hour period. This is a projection that would have been impossible 20 years ago, but it is now considered merely a routine preliminary to scientific forecasting.

All weather begins with four primary interacting elements. One is the sun, source of light and life, whose radiant energy ultimately determines the state of the atmosphere. Secondly comes the earth itself, whose unique geometry dictates the distinctive characteristics of weather and climate. The next element is the earth's atmosphere (from the Greek *atmos*, vapour, and *sphaira*, sphere), the envelope of gases that modulates solar radiation in its passage to earth. The fourth factor that shapes the weather is made up of the natural land-forms and geophysical features of the earth's surface—the mountains, valleys, oceans, ice-caps, deserts, lakes and rivers that alter the state of much of the atmosphere as it swirls incessantly around the earth.

The first of these influences on the weather, the sun, is a yellow-white star 865,000 miles in diameter and some 93 million miles from the earth. It is a fiery ball of exploding gases whose outer, luminous layer, or photosphere, registers temperatures between 5 and 6,000° C., and whose inner core is a flaming chaos where the heat may reach an unimaginable 18,000°. In volume, the sun is 1,306,000 times as large as the earth. Its weight is an estimated two thousand billion billion tons, about 333,420 times that of the earth. If the universe were shrunk until the earth was the size and weight of a table-tennis ball, the sun would still measure about twelve and a half feet in diameter and would weigh approximately three tons.

A hydrogen furnace

The central fact about the sun in relation not only to weather on earth but to all forms of life on earth is that it is a stupendous thermonuclear power plant. In this vast furnace, fusion "burns" hydrogen and converts it into helium. In the process the sun transforms part of its substance into energy that it radiates at the constant rate of 70,000 horsepower for every square yard of its vast and seething surface. To stoke this nuclear furnace the sun destroys four million tons of its own mass every second. It has been consuming itself at this rate for five thousand million years; it has the resources to keep it up, at the current rate, for at least thirty thousand million more.

If the sun's heat dropped by 13 per cent, it is estimated that the entire earth would soon be encased in a layer of ice a mile thick; if its heat increased by 30 per cent, it would cook every vestige of life off the face of the planet.

Of the vast amount of energy that the sun radiates into space, the earth intercepts only a tiny fraction—about one two-thousand-millionth. Yet this

fraction pours onto the earth a steady, unceasing 23 billion horsepower —more energy every minute than all mankind uses, in all forms, in one year. The sun beams this energy through space to earth as electromagnetic waves of three kinds, all of which are similar to radio waves, but shorter in length (an electromagnetic wave is measured, not the way an ocean wave is, from trough to crest, but by the distance between crests). The first kind, the ultra-violet rays, measure from 400 thousand-millionths to about 16 millionths of an inch in length; the second, the infra-red rays, measure from 30 millionths to 400 thousandths of an inch (the short wave of radio, by comparison, measures several feet in length). Neither the ultra-violet nor the infra-red rays can be seen by the human eye. In between them lie the wave-lengths of visible light, ranging from 16 millionths of an inch (violet) to 30 millionths of an inch (red).

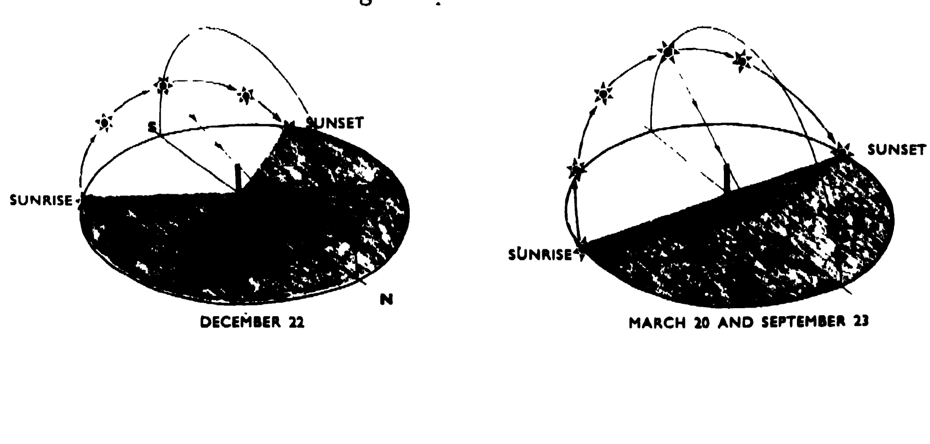
The method by which the sun's radiation is turned into heat will be discussed in detail later, but it is roughly comparable to the way a stone used to be transformed into a foot-warmer in pioneer days. The stone absorbed energy radiated by the camp fire. Then, placed inside the sheets, it re-radiated this energy as heat and gave the pioneer a snug, comfortable bed to look forward to. In similar fashion the earth absorbs radiant energy, often called insolation, from the sun, is warmed by it, and re-radiates this energy, in the form of heat, into its encompassing blanket of atmosphere.

An important change occurs in the process. The wave-lengths of terrestrial radiation going out are longer than those of insolation coming in—too long to escape or to bounce back readily through the atmosphere into space. Much of this radiation is absorbed by the water vapour in the atmosphere. It is this heat energy, garnered from the sun in the equatorial and temperate zones, that powers the complex circulation of the atmosphere, drives the winds, brews the cyclones and hurricanes, sets the sky crackling with lightning, creates and showers down on earth the blessed rains and furious snows that so directly affect man's existence.

The earth's contribution

Of course, the earth is not entirely at the meteorological mercy of the sun. As a member of the solar family, it has unique features of its own that contribute profoundly to the creation of its weather.

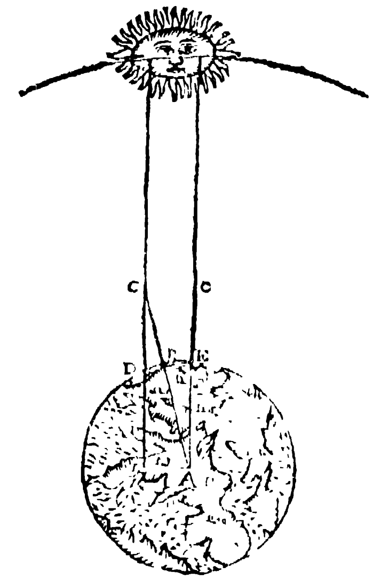
One is the fact that in addition to its annual 600-million-mile swing around the sun in its elliptical orbit, the earth rotates on its own axis, from west to east, at a speed at the equator of nearly 1,050 miles an hour. This west-to-east rotation also determines the prevailing direction of persistent winds and the prevailing direction of ocean currents, both of which contribute to making the weather what it is.



THE SUN CASTS SHADOWS that vary in length depending on the season, reflecting changes in the earth-sun relationship that cause seasonal variations in weather. The drawings show the shadows cast by a stick near Boston at about the time of the winter solstice, when the sun is farthest south (*left*), at the spring and autumn equinoxes (*centre*), when day and night (*shaded area*) have the same length; and at the summer solstice, when the sun is farthest north. The shadows lengthen in autumn and winter because the Northern Hemisphere is tilted away from the sun, decreasing the angle at which the sun's rays strike, and bringing shorter days and colder weather. In spring and summer, the sun's rays strike more directly and the weather warms up.

Another feature of the earth that influences weather is its shape. Isaac Newton, in the 17th century, proclaimed the earth an oblate spheroid —a ball, flattened at the poles—and modern geodesy, with the help of photographic measurements from artificial satellites, confirms the fact. This roughly spherical shape makes for sharp differences in the temperature in different parts of the earth. Just as a flash-light beam makes a sharp bright spot when it strikes a surface at right angles, but spreads out and dims when it strikes the surface at an angle, so the sun's rays strike with greater intensity at some parts of the earth than at others. The intensity of solar radiation is further affected by the fact that on a slanting course the sun's rays must travel through more of the atmosphere, and are thus more completely absorbed before reaching the earth.

Still another peculiarity of the earth's situation in space is its tilt with relation to the plane of its path around the sun. It is canted at a fixed angle of 23½°. This slant further modifies the angle at which the sun's rays strike the earth. It also accounts for four seasons, because entire areas of the earth are tipped towards or away from the sun for half a year at a time. Thus, in January, that same square foot of land at Anchorage receives only 9 per cent as much solar energy as it does in July. But in the Southern Hemisphere in January the sun is striking with full force; in that part of the earth the coolest part of the year comes during the northern summer.

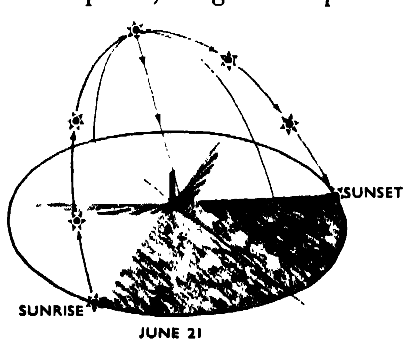


SUNLIGHT and its distribution over the earth are shown in this 17th-century illustration from a book by the German scientist Athanasius Kircher. Although he erred in having his sun revolve about the earth, Kircher, using geometry, determined accurately which parts of the globe would be light and which parts would be dark at a given time of the year.

The atmospheric blanket

Here, then, are two of the quantities that produce weather—that celestial furnace the sun and, 93 million miles away, the circling, tilted planet earth. There is a third element essential not only to the existence of weather, but to the existence of life itself. That is the invisible and indispensable stuff called the atmosphere. Without it, the earth would be a dead planet, as sterile and lifeless as the moon; there would be no trees, no animals or birds, no bright sky, no clouds or golden sunsets. Not only is it essential because all life breathes it; it is also a necessary protective blanket. Without it, the rays of the sun would scorch the earth's crust with temperatures as high as 80° C. by day at the equator. By night, the cold would reach an unendurable 140° below zero at the same place.

The atmosphere is a fluid mixture of gases surrounding the earth, encasing it in concentric layers of varying thickness and density. Insubstantial as it seems, it has ponderous mass. Held to earth by gravity, it weighs about 5,600 million million tons. At sea level, a vertical column of air, one inch square and extending to the outer reaches of the atmosphere, weighs 14.7 pounds; a column a foot square weighs nearly



a ton. On each human at sea level, depending on his size and the area of his skin surface, the atmosphere exerts a crushing pressure of from 10 to 20 tons. Men survive at the bottom of this sea just as fish survive at the bottom of theirs: inner body pressure, pushing out, equalizes atmospheric pressure pushing in. And to carry the comparison with the salt-water ocean one step further, the atmosphere, like the ocean, is heavier at the bottom, thinning out rapidly with increasing distance from the earth's surface. The air pressure that reaches nearly 15 pounds per square inch at sea level diminishes to only seven and a half pounds per square inch at 18,000 feet. Though its most rarefied frontier is hundreds or even thousands of miles out in space, all but 1 per cent of the atmosphere lies within a layer 19 miles thick around the earth.

Water in the air

The atmosphere is composed mainly of oxygen and nitrogen, but it also contains minute quantities (about .03 per cent) of carbon dioxide, which plays an important role in stabilizing temperatures both near the earth's surface and in the upper atmosphere. Various other substances are present as well—most notably, water vapour.

Water is, meteorologically, the most important constituent of the atmosphere of the earth. It is present up to altitudes of about 40,000 to 45,000 feet, in amounts ranging from about zero over some mountains and deserts to 4 per cent over oceans and seas. If all of it were condensed in liquid form, it would cover the entire surface of the earth with one inch of rainfall.

Water exists in the atmosphere in three forms: as an invisible, gaseous vapour; as liquid droplets, and as solid ice crystals. In the two latter states it comprises visible precipitation—rain, hail, sleet, snow.

The atmosphere wraps the earth in several distinct layers. First and lowest is the troposphere. The troposphere's thickness varies from 5 miles at the poles to 10 miles at the equator. Tropospheric air is heavy, its molecules densely packed. Though the troposphere contains the merest fraction of the total depth of the atmosphere, it contains 80 per cent of the total weight and virtually all the water vapour. It is the planetary cauldron of weather. Within the troposphere, humid air, heated by the ground beneath, boils heavenwards at the equator, creating vast, tropical updraughts. To the far north, ponderous masses of dry cold air sink earthwards. Horizontal wind currents howl across the ice-field at tremendous speeds. Surface temperatures, ranging from more than 40° C. over oceans and deserts to as much as 70° below zero at the poles, create a churning in the atmosphere that determines weather and weather patterns all round the world. In the troposphere, temperature decreases with altitude at an average rate of 2° C. for every thousand

feet—that is, with increasing distance from the source of atmospheric heat, the sun-warmed earth.

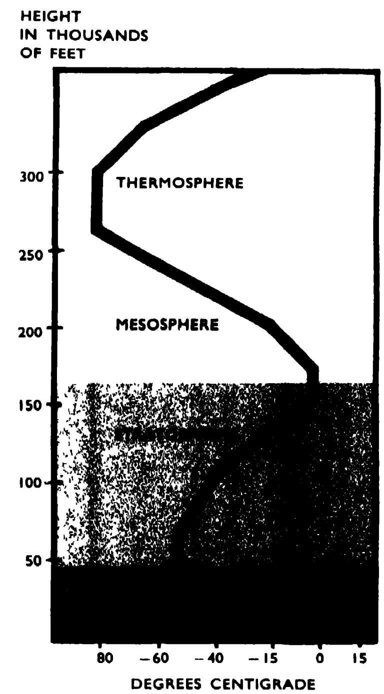
In addition to the sun, the earth's geometry and the atmosphere, one final factor influences the weather. That is the earth's geophysical landform—the mountain barriers, the oceans, the continents, the valleys, the lakes. What the weather is in any area today, or next month, depends a great deal on that region's landforms.

Land, for instance, both gains and loses heat more quickly than water does. Since water retains heat longer than soil, people living near a seacoast or large inland body of water experience cooler summers and milder winters than those who live far from the nearest ocean or lake. A resident of central New York State may board a plane for Boston, leaving behind several feet of snow and sub-zero temperatures, and discover that on the Atlantic Coast, in the same latitude, the weather is so mild that there is not even ice for skating. Similarly, the traveller who leaves Fargo, North Dakota, in the middle of June, with temperatures reaching 33° C., may, several days later, be shivering on the deck of a transatlantic steamer in precisely the same latitude—because the ocean still retains the icy chill of winter. Thanks to bracing winds off the cool Pacific, some 800,000 San Franciscans may work and sleep in a comfortable 15° C. in July while 90 miles north, in the breezeless oven of the Sacramento Valley, temperatures soar towards a scorching 45° in the shade.

Millions of people living along thousands of miles of coastlines benefit from this physical contiguity of land and water. It accounts for a cool sea breeze off the water during the day, and for the breeze that blows seawards off the land at night—major characteristics of the coastal weather pattern that, particularly in the tropics, makes life healthier and more pleasant than it would be otherwise. Sometimes it brings chill nights to even the most torrid locations. In Fiji, people are often forced to don overcoats at night for protection against the sudden cold.

The influence of mountains

Mountain ranges are also among the dynamic determinants of local and regional weather. In the United States, for example, the Mississippi Valley and Great Plains lie like a continental trough between the Rockies in the west and the Appalachians in the east. Wintry blasts from the north sweep down this trough as through a funnel. Clashing with warm, moist air from the Gulf, they generate the massive, eastward-moving storms and blizzards that frequently paralyse the densely populated areas of the nation. But mountain barriers can also protect a region from air movements that bring stormy weather. Along the French Riviera, the Maritime Alps shut out cold north winds. The result is year-round balmy weather, with scarcely a touch of frost even in January. Mean-



ATMOSPHERIC TEMPERATURE, contrary to popular belief, does not drop steadily as altitude increases. It does fall from ground level to the top of the troposphere, but in the stratosphere it rises—affected by the heat-absorbent form of oxygen called ozone. In the ozone free mesosphere the air cools. In the thermosphere it rises again.

while, Portland, Maine, in the same latitude but with the stormy North Atlantic on its doorstep, may have snow for half the year.

The most dramatic example of the effect of mountain ranges on regional weather, perhaps, is the orographic, or mountain-modified, wind which is discussed in greater detail later. In brief, this is generally a prevailing wind that crosses a high mountain barrier. As it ascends, it cools and its water vapour condenses into precipitation. On the other side of the mountain, deprived of its moisture, it reaches the valley floor as a hot, eye-stinging, throat-parching wind accompanied by other phenomena: a strange, crystalline clarity of air, extraordinary visibility, and lens-shaped clouds that form high in the air and to the leeward side of the ridge.

Everywhere in the world, whatever its beginning, whether affected by mountains or oceans, the weather exerts a powerful influence on mankind.

It can be a shattering force of ruin and desolation. But it can also be a patch of soft spring sky, a pattering of rain on thirsty leaves, a witchery of fog across the hills, a silence of snow over the city. Either way, it is part of man's life—a never-ending, ever-changing pageant created by sun, air and earth. It still has its mysteries, its secrets. But they are dwindling. Under the assault of science, they are fewer today than ever before.

Long-range Forecast—Variable

The essence of weather is change. In minutes, the sea can turn from brilliant calm to towering storm (*opposite*). A shift in the wind can change an Indian summer's day to a real foretaste of winter, ominous with clouds and bitterly cold. In hurricane season, the storm that tore through Key West yesterday may smash New England next week—or dissipate harmlessly in the North Atlantic. The same wet Pacific wind that dumps tons of snow on the western slopes of the Rockies slides down the mountains' eastern slopes as the warm, dry zephyr that thaws the snow-bound prairies. From day to day, or within the longer swings of seasonal change, man may be hurt by flood or drought, cheered by healing rain or morning dew, terrified by hurricane, blizzard or tornado—all because the earth is cloaked in a veil of atmosphere which is seemingly insubstantial, but whose constant movements affect him every moment of his life.

SUN-GILDED STORM CLOUDS

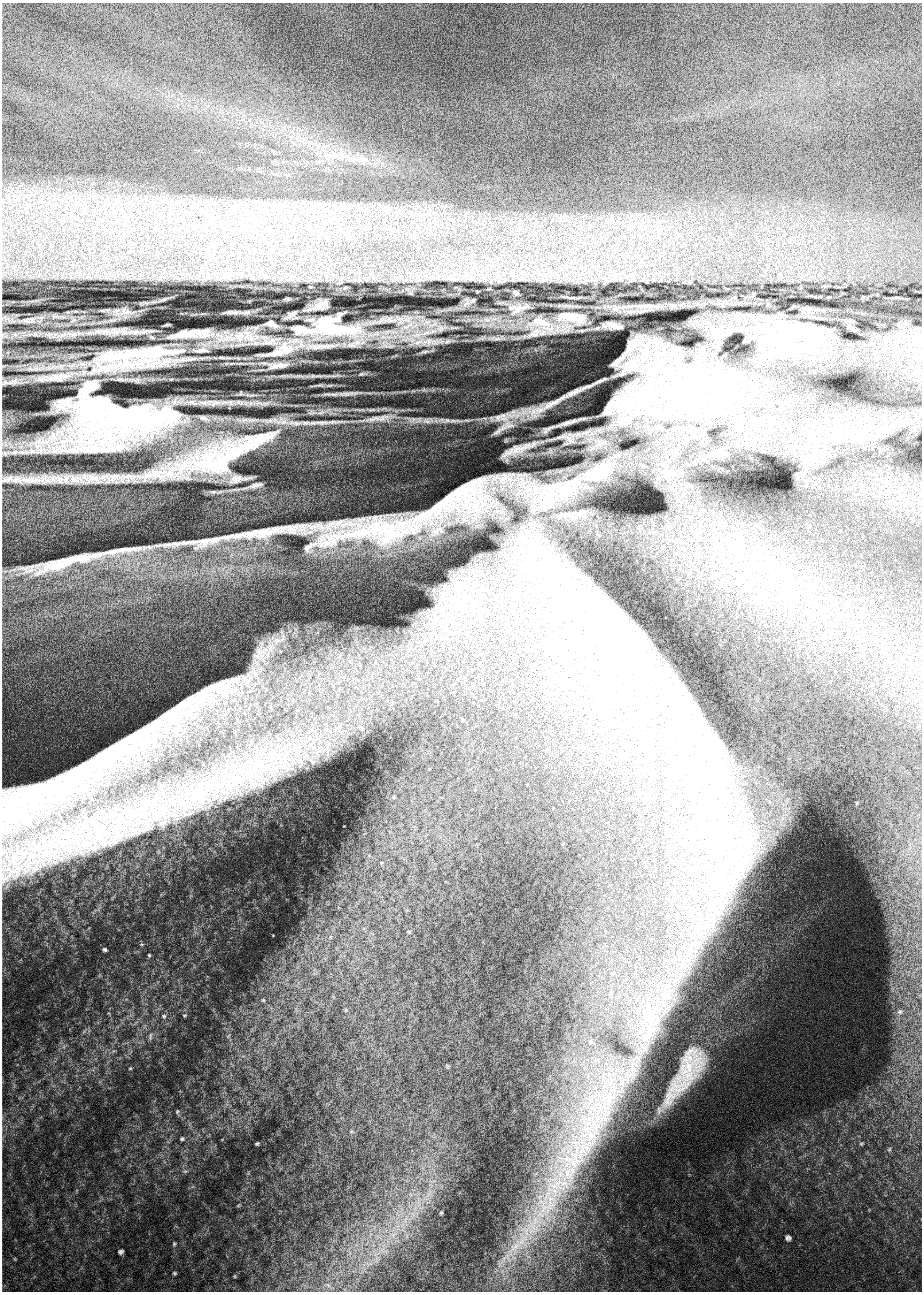
In a dramatic illustration of the changing nature of weather, the towering clouds of an early-evening rain-storm obscure the sun off Bermuda. This photograph also illustrates the cyclical nature of weather involving sun, air and water. Heat from the sun evaporates water, which forms clouds. The clouds cool and eventually return the water to earth in one form of precipitation or another.

The Prime Movers: Fire and Ice

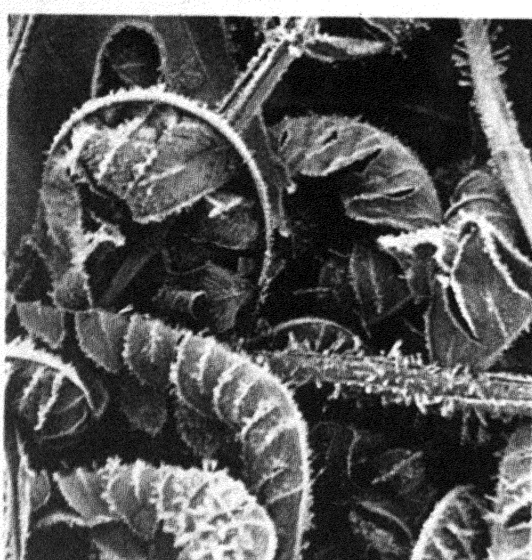
Over the tropic sea near the Hawaiian Islands, the blistering sun beats down day after day, heating the air, evaporating the ocean water. Half a world away, the frozen poles are covered with ancient ice. At any given moment the temperature differential between these thermal extremes may be as much as 100° C. The air distance that separates them is some 12,000 miles. Yet, remote as these areas of the planet are from one another, there is an unceasing interchange between them: through the medium of the atmosphere, tropical winds are constantly transferring their heat to cooler air masses coming from the poles. This heat transfer is the fundamental cause of all the varieties of weather shown on the following pages.

SUNSET OVER THE NORTH PACIFIC

A FROZEN ICE FIELD IN ANTARCTICA



DEW SPARKLES ON A WOODLAND PLANT



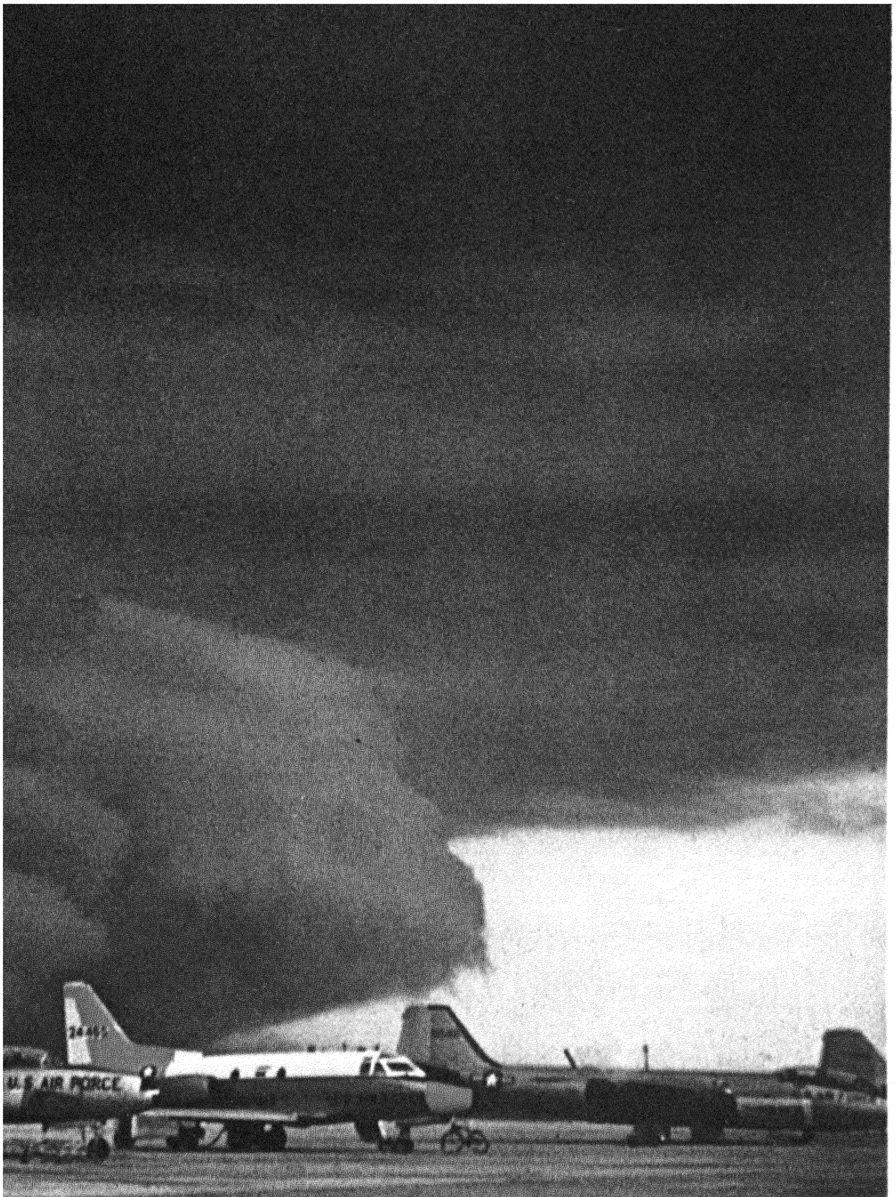
FROST CLOTHES OAK LEAVES AND FERNS

FOG FILTERS THROUGH AN ENGLISH FOREST

The Evening Dews and Damps

Water vapour—gaseous and invisible—is always present in the atmosphere, even in the air over the poles and the driest deserts. At various times and places it may condense as the result of cooling, which can occur in a number of ways. The least spectacular takes place at the very surface of the earth. With the coming of night, the ground yields up the day's heat. The temperature of the earth drops, and airborne water vapour condenses to form either dew or frost, depending on the degree of cold. Closely akin to these two is fog, which is condensation, not on the surface of the earth, but on invisible particles in the air.


U.S. AIR FORCE
TR-179
U.S. AIR FORCE



The Spectacle of Cloud and Rain

A single thunderstorm (*bottom*) is a spectacle. But when they are massed into an ominous advancing squall line (*top*), thunderstorms assume the terrifying appearance of a huge black tidal wave. A squall line, composed of dozens of thunderstorms, is similar to a rank of soldiers advancing abreast. These storms are a meteorological mystery. They form, no one knows why, 50 to 250 miles in front of a cold front that is pushing into warm, muggy air. Like a shock wave, the squall line strikes, usually with violent winds and rain—and 20 minutes later has passed on, leaving the weather exactly as it was before. But squall lines are one of weather's surest signs of change. Within hours, cold air will follow and overrun the region.

A SQUALL LINE BEARS DOWN ON PATRICK AIR FORCE BASE IN FLORIDA (TOP)

AS IF ON AN IMMENSE STAGE, A DARK CURTAIN OF RAIN CLOSES ACROSS A FIELD IN SOUTHERN NEW MEXICO

Rain Measured by the Foot

The coming of rain to the monsoon belt of South-East Asia is among the most dramatic natural phenomena. For six months, roughly from January to June, dry winds blowing from the north-east off the Gobi Desert parch the region, sucking moisture from the soil. Then one blessed day in June, sometimes in the space of only an hour, the wind may veer a full 180°, and begin to sweep inland from the south-west, bearing with it moisture off the Indian Ocean and the Bay of Bengal. These cool, moist monsoon winds, moving across the scorched earth, are suddenly pushed upwards by convection currents. The result is rain, often in torrential amounts. At Cherrapunji, near the Burmese border, average annual rainfall is 436 inches—more than 36 feet.

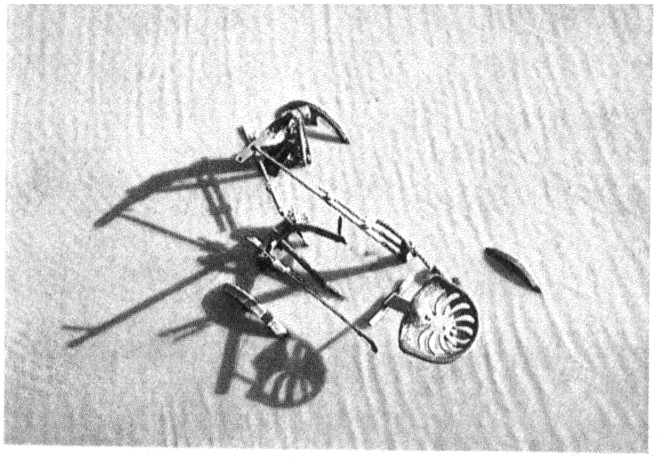
PILGRIMS GATHER AT A RELIGIOUS FESTIVAL TO GIVE THANKS FOR THE MONSOON RAINS

The Curse of Too Much Water

Weather in excess often brings disaster. Wild winds can ravage coasts. Blizzards may paralyse vast areas. And rain in amounts too great for the land to handle may cause floods.

In a few cases, floods may be beneficial, such as the yearly flooding of the Nile that follows the run-off of melted snows from the Ruwenzori Range and spring rains. Other annual floods, notably in the Mid-West, are often of disaster proportions.

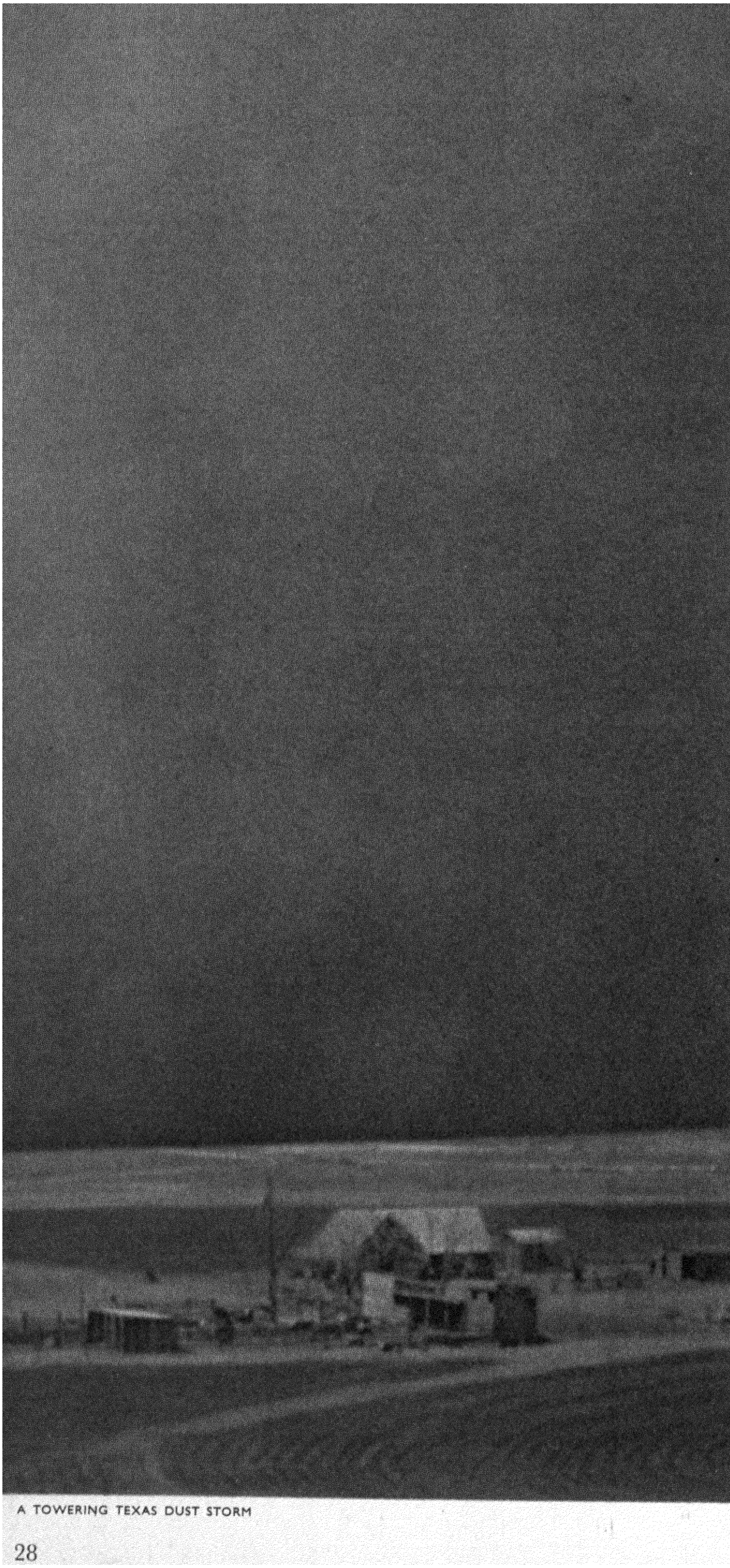
But the most devastating floods are the terrible flash floods, which follow violent rainstorms. The damage and death caused by such floods result from the fact that they are unexpected. In 1955, New England was caught by a downpour that brought 14 inches of rain in one day. The river Connecticut rose 19½ feet, pouring over its banks. When the storm had passed, 186 people were dead, and property damage was over £700 million.



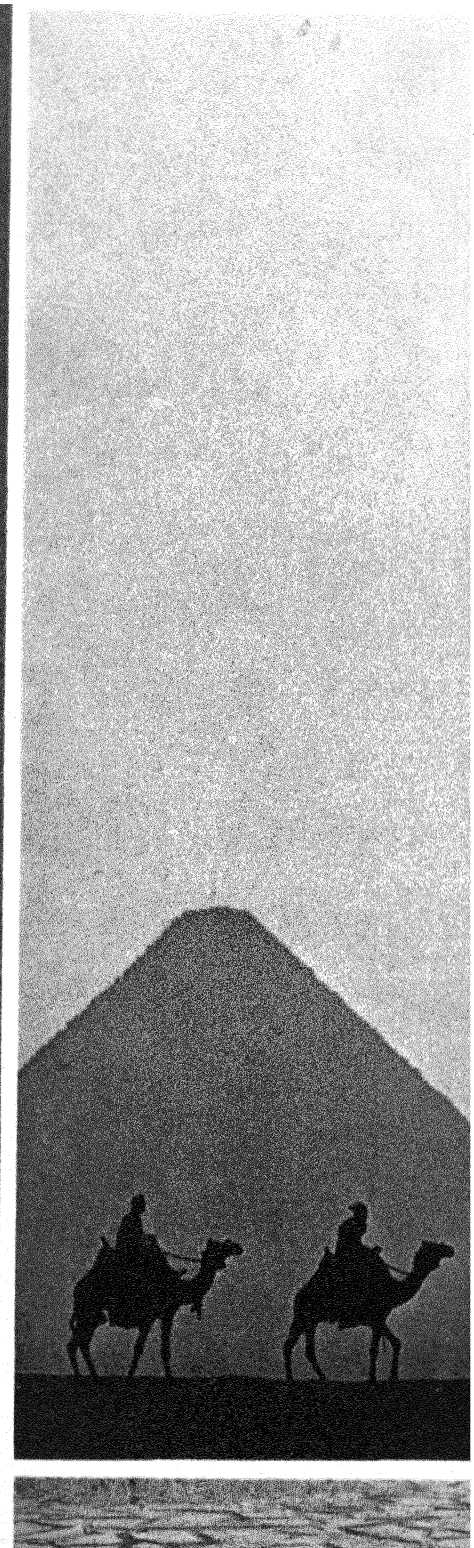
VALLEY OF THE RIVER HUNTER, AUSTRALIA

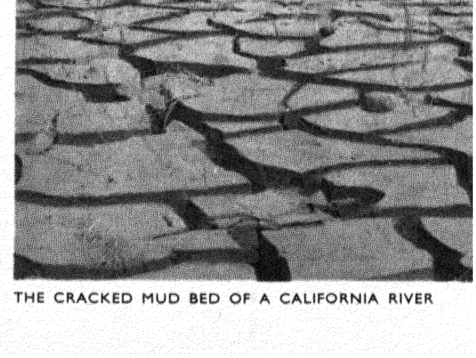
WATERS FROM THE RIVER FEATHER IN YUBA CITY, CALIF

RIVER MAHANADI, INDIA



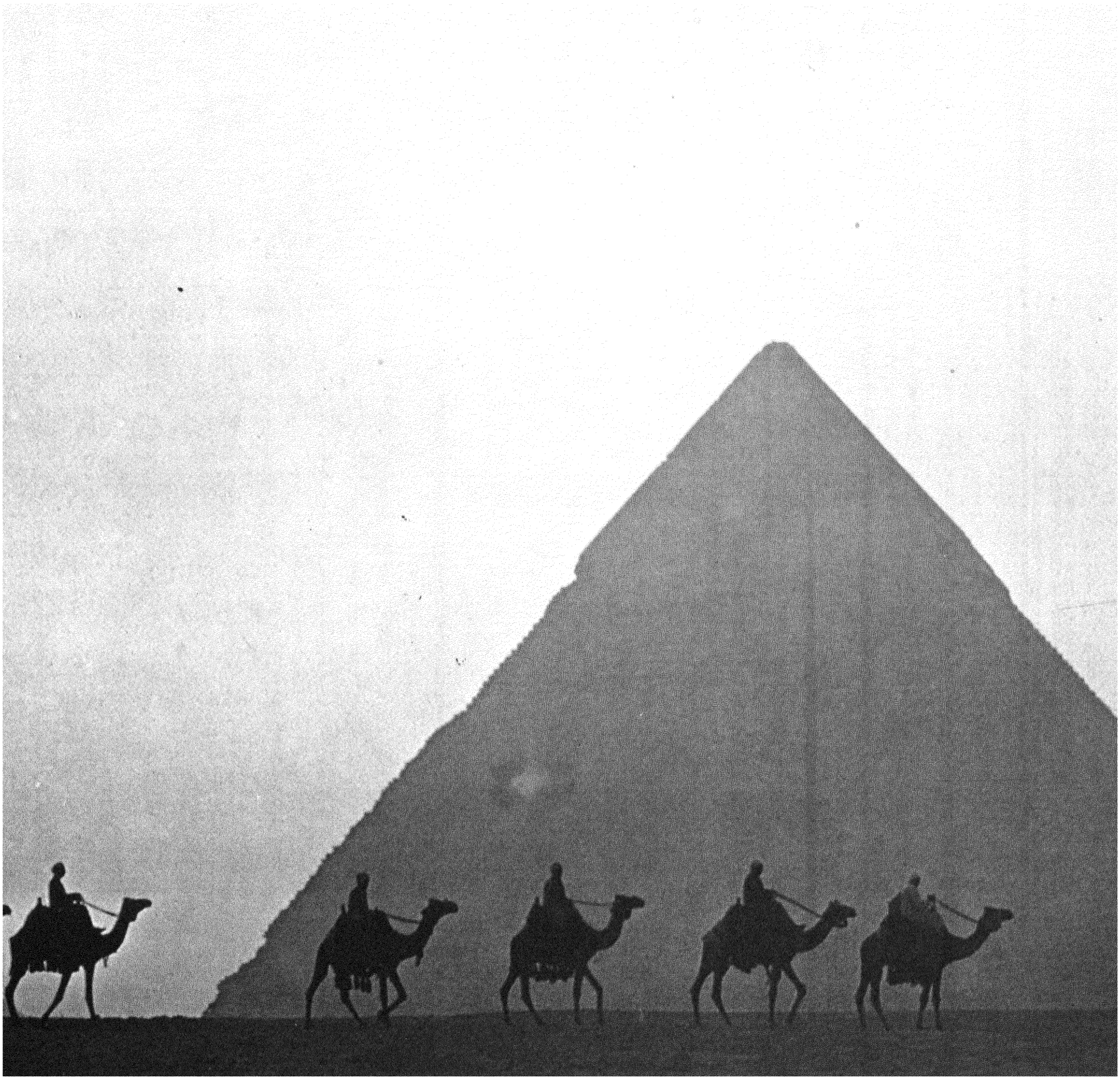
A TOWERING TEXAS DUST STORM





THE CRACKED MUD BED OF A CALIFORNIA RIVER

A CARAVAN CROSSING THE SAHARA, WHERE THE RAINFALL IS ONLY TWO INCHES A YEAR



The Scorching Assault of Drought

The face of dry weather is harsh. Its cruelty is revealed on these pages (*from left*) in the deep, malignant red of a dust storm in the American West, the metallic glare of an Egyptian desert, the tortured fissures in an empty river bed. The winds of drought are carriers of dust and sand, and local people often give them proper names, like personal enemies. Egypt has the *haboob*, a wind that lifts dust to great heights. Arabia's windy plague is the *shamal*, which drives sand through the air at 40 miles an hour. The horror of this storm has been brilliantly described by T. E. Lawrence. In the "breathless wind", he wrote, "our faces chapped, while our eyelids, gone granular, seemed to creep back and bare our shrinking eyes."

STORM-DRIVEN WAVES BATTER THE WATERFRONT OF PROVINCETOWN, MASSACHUSETTS, IN AUGUST

The Atmosphere's Safety Valve

A man beset by a great storm such as the one shown above lambasting Provincetown, Massachusetts, thinks of the storm's explosion as purposeless and destructive. But to a meteorologist, even the most destructive storm has a purpose: the release of excess energy through a safety valve. Just as a ship's boiler would explode if steam pressure were allowed to build up indefinitely, so energy released by the interaction of hot and cold air would reach fantastic levels if it did not dissipate regularly. Then, when it did explode, the resulting storm would be utterly catastrophic.

The Atmospheric Engine

SUN, EARTH AND ATMOSPHERE together constitute a stupendous engine for the production of weather. The sun is the furnace, turning fuel into radiant energy. The earth's warmer regions are the boiler, where the energy is converted into useful heat. The heat sets the giant envelope of atmosphere in motion, to perform the work that we call weather.

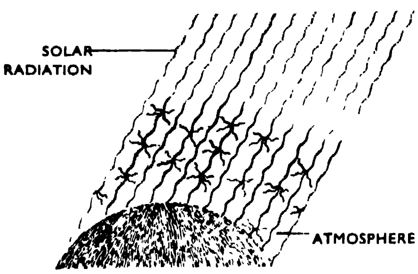
What sort of work does the atmosphere do? It is an extravagantly inefficient machine: only 3 per cent of the energy it receives is converted into energy of motion. Yet this is more than enough to move things about. In Trowbridge, a man running in from a heavy storm heard sounds as of mud plopping on the pavement behind him. He turned round and saw hundreds of tiny frogs falling from the sky. A thunderstorm in Providence, Rhode Island, delivered live fish, strewing them over a quarter of an acre. A storm in Worcester, in 1881, poured crabs and periwinkles into the streets by the bucketful. This storm has a particularly respected place in the annals of meteorology, for Worcester is 40 miles from the sea.

Transporting periwinkles 40 miles through the air is the kind of work the atmosphere does with ease. It does more difficult work as well. It is perpetually moving its weight of some 5,600 million million tons, some of it at jet-stream speeds of 200 to 400 miles an hour. The estimated 500 million tons of topsoil borne off by the wind during a single storm in Nebraska and South Dakota seem trivial compared with the quantities of water the atmosphere carries at all times. A single small, fluffy cloud may hold from 100 to 1,000 tons of moisture. On a hot afternoon, the atmosphere evaporates water from the Gulf of Mexico at the rate of 5 thousand million gallons an hour, hoists it up and carries it off to the north-east by the millions of tons, to release it later as rain over New York and southern New England. A polar air mass moving south from Canada may pick up nine gallons of water from the Mississippi drainage basin for every gallon that flows from the mouth of the river Mississippi itself. It may then carry this moisture over the Gulf and deposit it as rain to even the account for what was removed earlier.

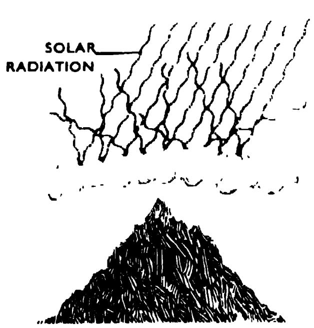
The energy involved in these atmospheric chores is prodigious. A summer thunderstorm squanders in its profligate lifetime as much energy as a dozen or so Hiroshima-type bombs—and 45,000 thunderstorms are brewed around the earth every day. A hurricane releases almost as much energy in one second. Weather, whether it hurtles periwinkles, blows down houses or merely bends the grass, is the display of energy.

Weather has a reputation for being capricious, but like all manifestations of energy, it follows physical laws. Local and even global weather predictions are difficult partly because the engine creating weather is so huge and has such a profusion of parts. But we have weather in the first place because of a basic principle of physics: energy is convertible with-

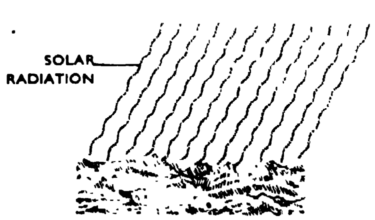
HEAT AT THE TOP
An otherwise blue Pacific is marked by a patch of clouds in this picture taken 100 miles up by an astronaut. An island beneath the clouds radiates much more heat into the air than the surrounding water does. As the air rises and cools, its water vapour condenses into clouds. In microcosm, this illustrates the heating, lifting and condensation that produce weather.



SOLAR RADIATION, which creates weather, is acted upon in several ways by the earth. In the diagram above, it is scattered by air, dust and water vapour. More blue light is dispersed than any other colour, accounting for the tint of the sky



INCOMING RADIATION is reflected back into space by clouds and the earth's surface Clouds turn back some 25 per cent of all incoming radiation. Part of this is visible from outer space as a brilliant glow, or "earthshine", of blues, greens and whites.



ABSORBED RADIATION, about half of the total, is converted into heat upon striking the earth. This heat evaporates water from the oceans and warms the lower atmosphere, thereby providing the essential ingredients that produce the world's weather.

out loss. That is, energy may take many forms, changing from radiation to heat to motion, but once it is created, it cannot be destroyed.

Solar energy, discussed in detail in the preceding chapter, is composed of radiations in many different wave lengths. Some 23 billion horsepower reaches the earth's upper atmosphere continuously. As the assorted wave lengths pass through the atmosphere, they meet varying fates. Some are scattered as they bounce off molecules of air, water droplets or microscopic particles of dust. Other rays cannon intact off the tops of clouds and are reflected back into space. Nearly half the incoming solar energy is lost to earth by reflection.

But more than half the supply of energy is still available to be absorbed. Air is a poor absorber of radiant energy, and only 15 per cent of the solar energy is absorbed by elements in the atmosphere—by dust and certain atmospheric gases such as water vapour, ozone and carbon dioxide.

The rest finally reaches man's level. Much of it is in the form of light. It has travelled 93 million miles, performing, as far as we know, very little work along the way. But now it strikes the many surfaces of earth—a body of water, a furrowed field, a leaf, a cheek. Highly reflective surfaces like a polar icecap or a glass sky-scraper turn some of it back with a blinding glare, adding to the total reflected back into space. Some of it is also absorbed by plants and used in the chemically complex processes of growth. But most of the surfaces absorb it—and put it to work at last.

The radiant energy is converted into the energy of molecular motion. As the sun's radiation strikes houses, people, land and oceans it sets molecules dancing. This is the form of energy we call heat. The faster an object's molecules move, the warmer it feels to the touch. At absolute zero (−273.1° C.) there would be no molecular motion. The molecules of an ice-cube are relatively quiescent. But a tin roof on a sunny day is an invisible tempest of molecular activity. As its molecules move, continually receiving more energy, they throw off some of it in the form of long infra-red rays. Thus all over the earth, various surfaces transform the sun's short waves into long infra-red waves, which excite any molecules that intervene into increased activity. These are felt as radiant heat. The earth itself is thus transformed into a giant radiator of heat.

Engineered for confusion

But unlike a sensibly engineered radiator, the earth radiates heat unevenly. Rivers, mountains, shores and plains cause local differences in heat production. Boston swelters while Cape Cod registers a pleasant 21° C. Denver remains warm while blizzards rage on the mountain tops a few miles away. On a global scale, winter and summer, day and night, the land and the oceans, the equatorial regions and the polar regions all cause temperatures to rise and fall at different times, in different

places—and this causes complications for meteorologists.

The uneven distribution of heat sets the great machinery of the atmosphere in motion. The net effect of this motion is to distribute the heat more evenly around the world. This, as simply as anything, summarizes the plot of the drama of weather. Warm and less warm air move and mix—vertically, horizontally, often turbulently, in all directions. In broad strokes, warm equatorial air moves towards the poles, and cold air from the poles moves towards the equator. This basic movement creates our intercontinental winds and systems of weather. The balmy air of a January day in California was warmed over the mid-Pacific, a cold snap in New Jersey began over the barren ground of Canada.

The puzzle of heat

For centuries the nature of heat was one of the great puzzles of the natural world, and all sorts of experiments have contributed to the solution of its mysteries. Probably the earliest men to build fires noted that smoke rises, and common observation also taught that warm air mixes with and gives some of its heat to cooler air. The early Greeks knew that air expands as it grows warmer and contracts with cooling.

Galileo Galilei, applying this principle, invented the first thermometer about 1600. His "thermoscope" consisted of a thin glass tube a foot and a half long. It was blown into an egg-sized bulb at one end, but was open at the other. Galileo warmed the bulb in his hands, then placed the open end in water. As the bulb cooled, the air inside contracted, and water pushed partway up the tube. From this level, the column of water rose or fell with every change of temperature. With the addition of an arbitrary scale, it became a crude thermometer. Later experimenters refined it and created the standard scales that are now in use.

By the 18th century, the properties of heat were being seriously studied. Scientists used concave mirrors to focus the rays from a heat source and beam them across a room, sometimes as far as 24 feet away, magically igniting a spoonful of sulphur or a small pile of tinder. One scientist found by careful measurement that it takes longer to bring water to a boil in a brightly scoured pot than in one whose outside surface is blackened with soot. His explanation was that a shiny pot reflects "particles of fire" —not a bad approximation of the truth, which is that a shiny surface reflects heat, while a blackened one absorbs it.

The results were all very puzzling. Heat moved invisibly through space, it travelled in straight lines and it could be reflected. The theory was widely held that heat was an invisible substance, called "caloric", that flowed from a warm body into a cooler until equilibrium was reached.

In 1798, however, an American Tory expatriate, Benjamin Thompson, later Count Rumford, brought the caloric theory into question. He had

noticed, in the course of his military career, the intense heat generated by friction when a brass cannon was bored by drills. He had a brass cylinder drilled under gallons of water whose temperature was 15° C., and much to the astonishment of spectators, the water eventually came to a rolling boil. It was hard to believe that sufficient "caloric" could have been squeezed out of the brass to boil water. The cylinder and bored-out scrap were carefully weighed; together they weighed precisely the same as the intact cylinder before boring commenced. Moreover, the supply of heat had been apparently inexhaustible. This, to Count Rumford, was the most significant point of all. He declared firmly, "Anything which any insulated body . . . can continually furnish without limitation, cannot possibly be a material substance". Heat could not be "caloric"; he strongly suspected that it was related instead to the movement of the drill biting into brass.

In the 19th century, a succession of physicists began exploring the connection Rumford had hypothesized between heat and motion. The English physicist James Joule raised the temperature of water by churning it with paddle wheels. While on his honeymoon in the Swiss Alps, he was seen gingerly climbing a mountain while carrying a large, specially constructed thermometer– so that he could measure the temperature of a waterfall at both the top and the bottom of its fall. Joule helped to prove conclusively that Count Rumford was right. Heat was soon determined to be the manifestation of molecular motion. And the study of modern meteorology is the study of how this molecular motion generates the movement of winds and all the other work that weather performs - which in turn helps to distribute heat to all the quarters of the globe.

A watery trap for heat

Earth's weather can be said to begin around the earth's middle. The tropics receive vastly more solar energy per square mile than the polar caps. If all the earth's atmosphere were clear and dry, the heat radiated from all the earth's surfaces, including that from the tropics, would pass very quickly back into space. But three-quarters of the earth's surface consists of water, and the skies overhead are loaded with water vapour to varying degrees. This water vapour is a special blessing, indispensable for life on earth. Although oxygen and nitrogen are poor absorbers of energy, water is a good one. Heat emanating from land and ocean is absorbed in abundance by vapour and cloud droplets, and re-radiated back to earth.

This giant tennis game played with infra-red rays is called by meteorologists the "greenhouse" effect, for water in the air performs somewhat the same function as the glass roof of a greenhouse: it lets through incoming light and ultra-violet rays, but traps outgoing infra-red waves. Thus the equatorial regions in particular become a kind of giant boiler room, build-

ing up more heat than they radiate off into space. The heat's ultimate outlet is in the polar regions, which send back into space more radiant energy than they originally receive from the sun. Eventually, every bit of the earth's daily receipt of solar energy is restored to space; the earth's average temperature remains a constant 14° C. But the surplus heat from the boiler stays on earth long enough to go to work before it escapes, making the earth's northern and southern latitudes more equable.

Movable stores of energy

Water-soaked atmosphere not only bounces infra-red radiation back to earth, it also stores energy. Water vapour, moved by winds, is one of the atmosphere's most important vehicles for the transportation of heat. As solar energy strikes and penetrates water, the water is warmed below, but the exposure to energy on the surface is particularly intense. The millions of tons of water borne aloft from the Gulf of Mexico represent untold numbers of molecules set in such violent motion that they are torn free from their fellows, or evaporated. In other words, they have absorbed enough energy to keep other molecules at a distance; and the liquid water is converted to a gas.

This vapour exists to some degree in all skies. The vast amount of energy it carries is called "latent heat", because it is converted back into heat when the vapour condenses back into a liquid. Every time air is cooled sufficiently, its vapour condenses into clouds, composed of tiny water droplets—and heat is released into the atmosphere.

Air from the coldest northern seas bears a small amount of this latent energy. The moisture in a Maine sleet storm represents some of the solar energy that reached waters off Labrador. The storm is apt to be brief, and the heat it releases is lost high above the earth.

The moisture-laden winds from the south, however, shed vast amounts of latent heat as they move north; as they cool off they precipitate heavy rains and snows. (The heaviest snowfalls in the U.S. occur when the temperature is between −1° and −2° C.) One meteorologist has calculated that an inch of rain over an area releases as much energy as three days of sunshine falling in the same area.

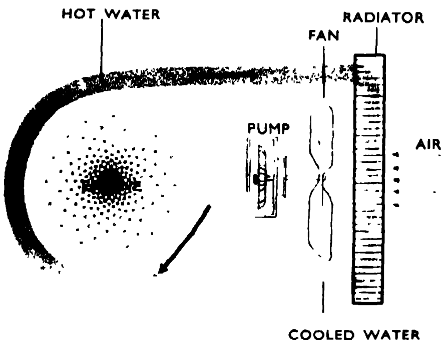
Moist air, then, carries great stores of latent heat. It is the work of the heat engine to spread this supply about. The atmosphere performs this task of heat exchange by sheer movement—known as convection.

Man has always known that air moves, and that hot air moves upwards. Today we know that air moves because some parts of it have more energy than others—i.e., are hotter than others. As air is warmed, its molecules become agitated and push away from one another. The air expands. As it expands, its population of molecules per cubic inch becomes less. Atmospheric pressure at any given point is the measurement of the total

GALILEO'S PROTEGES, Vincenzio Viviani and Evangelista Torricelli, organized the Academy of Experiments in Florence. There, eminent Florentine scientists carried out notable experiments in the measurement of temperature and atmospheric pressure. The instruments (*foreground*) were made for the Academy by the famous Florentine glass-blowers, and included an intricate and accurate spiral thermometer (*left*), and (*second from right*) an early hygrometer

weight of air above it. Because of its lesser density, a column of hot air weighs less than an equal column of cold air, exerting less pressure. As hot air expands, the cooler air next to it, under greater pressure, pushes sideways, forcing the warmer air in the only direction it can go--up.

Differences in temperature create imbalances in pressure, and unless an extraneous factor intervenes—a Himalayan peak, for example—horizontal imbalances in pressure cause an inexorable flow of air from the area of higher pressure to the area of lower pressure. In a small room with a pot-bellied stove in the middle of it, this flow becomes a neat, self-sustaining cycle. The air around the stove is pushed up, pushed along the ceiling by the flow of air behind it, cooled on its journey as its heat is radiated and conducted to cooler ceiling and walls, and eventually contracts and sinks floorwards, to rush like a moth towards the area of lesser pressure near the stove.



THE TRANSFER OF HEAT in the atmosphere is explained in part by this diagram of an internal-combustion engine. Most car engines are water-cooled. The water, pumped into a jacket surrounding the hot cylinders, absorbs the engine's heat, and is returned to the top of the radiator. It moves down through the honeycomb of metal, transferring its heat to cool air drawn through the radiator by the fan. This process is basically analogous to atmospheric circulation. Hot tropical air flows to the polar regions to be cooled. It then moves back towards the equator, where it is reheated. Without this circulation, the tropics would become unbearably hot, the poles unimaginably cold.

Riding high for a slow fall

In the atmosphere, this cycle occurs on an enormous scale, and in a far from simple fashion, between the earth's equatorial regions and the frigid areas of the poles. Air is hot around the bulging centre of the earth—the place where the most solar energy strikes, the place where the most heat is trapped by water vapour, the place where a description of weather must begin. The air expands, is pushed up and spreads northwards or southwards. Far below, cold air travels towards the equator to take its place. The body of warm air, perhaps 5 to 10 miles high, moves out into the areas of lower pressure. Cooling and sinking, it goes on a long, adventurous journey, at last coming to earth again far to the north or south. Cold, dense and dry, it starts to push its way back to the equator.

Convection moves heat from tropics to ice-caps, and in countless places in between as well. Convection is the sea breeze that blows in towards the hot land by day, and the land breeze that heads out to sea at night, after the earth has radiated off much of its heat. Convection sends air blowing up a sunbaked mountain by day, and brings the cool mountain air down to the warm valley at night. On small scale or large, whether it is moving from walls to stove, from sea to land or from pole to equator, the net effect of convection is to move air from cooler places to warmer, and to transfer heat from warmer places to cooler.

Yet, simple as this circulatory principle of convection sounds, in practice it rarely works smoothly beyond the threshold of that small, stove-warmed room. Winds and landscape can turn things topsy-turvy and place dense air on top of lighter. Air pressures are far from neatly graduated north and south from the equator. The earth's rotation skews rivers of air from north and south to east and west. Differences be-

tween land and water, day and night, cause abrupt temperature changes. Smooth sheets of air do not flow majestically from equator to poles and back. Rather, the air is driven astray by random irregularities. Units of air are generated, collide and merge. Heat exchange takes place in brawling currents, rapids, whirlpools and eruptions of the ever-restless atmosphere.

The largest units of air are those called air masses. If a body of air hovers long enough over a large, distinctive geographical feature, like an ocean, it tends to take on the temperature and moisture characteristics of the surface below. An air mass may cover several million square miles. It can be described as a coherent mass because its temperature and moisture-content are fairly uniform at any given altitude; and once it starts to move, it moves as a body.

Air masses are among the most important moving parts of the atmospheric engine. Throughout the world there are some 20 source regions for such masses of air. Air masses heading north meet and interact with those heading south in the temperate zones, giving the latitudes of the U.S. their changeable and much-criticized weather (the weather that caused Don Marquis to remark, "Don't cuss the climate—it probably doesn't like you any better than you like it").

The U.S. is visited chiefly by three basic kinds of air masses. Maritime tropical air (designated m*T* on weather maps) is heated by the sun beating on tropical waters. It is crammed with latent energy, which occasionally explodes as a hurricane. Much of the warmth reaching the U.S. comes from these water-laden masses, moving north at the rate of 400 to 500 miles a day from the mid-Pacific, the Gulf of Mexico or the Caribbean Sea.

Continental polar air (c*P*) delivers most of America's cold. Originating over Alaska and northern Canada, it is poor in latent-heat energy, dry as well as cold, and in winter or summer brings the blue skies of good weather.

Maritime polar air (m*P*) originates over northern waters in the Northern Hemisphere, and has more latent energy than continental polar air. It brings North Atlantic gales to the north-eastern States, and piles snow on the west, or windward, side of the Cascade Mountains in Oregon and Washington.

Characters waiting in the wings

These are the main characters in the daily drama of temperate-zone weather. U.S. residents know them well, for they give not only wide contrasts of weather from north to south, from Mississippi delta to Minnesota forests, but also the essence of temperate-zone weather—mercurial change. Tropical and polar air masses meet and do battle over

our heads. Often, not even the weatherman knows which one will win. The chief of the U.S. Weather Bureau made a celebrated slip in 1909, when he predicted clear weather for President Taft's inauguration and the ceremonies were caught in a howling snowstorm. His resignation did not solve the problems of the U.S. Weather Bureau. In 1916, a Congressman proposed abolishing the Bureau on the grounds that one of his constituents made better weather predictions with a sourwood stick. Unfortunately, both the constituent's name and his invaluable sourwood stick have been lost to history.

Every once in a while a northbound mass unexpectedly holds off a southbound one—or the other way around—ushering in an Indian summer in October, a thaw in February or a week of cool nights in July. The collisions and interactions of air masses generate winds, rains and thunderstorms from Cape Cod to San Francisco. Temperatures in Chicago or Butte typically shuttle over a range of 40° in any given month: they usually vary that much within a week, and often within a single day.

As Mark Twain warned, "Weather is a literary specialty, and no untrained hand can turn out a good article on it". The transfer of the world's supply of heat that produces weather is cumbersome, inefficient and turbulent. It is the bane of the weatherman; for the rest of us it is sometimes a sower of despair, and sometimes a delight.

Man against Hurricanes

The hurricane—sometimes called typhoon, willy-willy, *baguio* or tropical cyclone—is nature's most destructive force. A whirling windstorm of enormous power that is spawned mysteriously and suddenly in the otherwise gentle-weathered tropics, it goes roaring northwards to wreak its capricious will across thousands of miles of sea and shore. In the Atlantic and Caribbean, about 10 hurricanes are born every year. Since 1900 they have cost the lives of 12,000 U.S. citizens and destroyed some £5,000 million of U.S. property. The loss might have been less if men knew more about hurricanes—why, when and where they are formed, and why they veer in the directions they do. Weathermen are making urgent efforts to solve these puzzles, so that they can give warning early enough to allow citizens to batten down or flee. One day, perhaps, man will know enough about hurricanes to stop or steer them. Until then, about all he can do is take cover.

MAN MEETING HIS MATCH

A lone man rocks off balance as a hurricane batters the water-front at Palm Beach, Florida. When this picture was taken, winds were blowing at 100 miles an hour, with highest winds still to come. At a storm's peak, winds may hit 150 to 200 miles an hour—striking with such force that clothes are ripped from people's backs, cars swept from roads, trains brushed off their tracks.

TO THE ORDINARY MAN, wind may be many things—a balm or a scourge, an annoyance or a blessing. But to the meteorologist, it is air in motion. As such, it is energy. It streams in silent rivers across the sky, surges in invisible cataracts over mountain ridges, boils heavenwards over hot deserts and humid rain forests, swirls in furious, catastrophic maelstroms over Kansas, and the Caribbean and China Seas. It is power of cosmic magnitude. Scientists have estimated that if all the earth's atmosphere were moving at a leisurely 20 miles an hour—the speed of a light breeze—its energy at any one moment would equal the energy generated by the Hoover Dam operating at full capacity, night and day, for 6,680 years.

The wind energy performs prodigious tasks—tasks essential to the maintenance of the atmosphere's activities. It fills the sky with clouds, then sweeps it clear again. It drives the cooling, moisture-laden fogs in off the sea. It blows entire storm systems half-way around the world, moving heat and moisture from one region of the earth to another. It air-conditions and ventilates cities that lie along great bodies of water, like San Francisco and Chicago. It helps to push the ocean currents on their global journeys. It sculptures sand and snow, scatters seeds and spores. It clears the heavens of the poisonous exhalations of our machines and factories.

What makes the wind blow? And why does it blow first this way, then that—now weak, now strong? The answer is, uneven atmospheric pressure. Because there are always differences in the temperature of the atmosphere, there are also pressure differences, and these differences naturally seek to balance themselves. High-pressure air in a child's balloon, when released, rushes outwards to join low-pressure air. Air under 30 pounds of pressure in a tyre may, if the tyre has a weak spot, burst through to meet the average 14.7-pound pressure of the surrounding atmosphere. Similarly, wind movement is caused by the forces acting to push air from higher to lower pressure.

Men always guessed—and later knew—that the wind carried messages about future weather. Wind from one quarter meant fair weather, wind from another, storms. And so they watched the way trees bent, the way smoke drifted. They wet a finger and held it up; the cool side faced the wind. In ancient times, as today, the wind was named after the direction *from* which it blew. "Out of the south cometh the whirlwind", says the Book of Job. But steady south winds also brought hot weather to Biblical lands. "When ye see the south wind blow, ye say, There will be heat; and it cometh to pass", wrote St. Luke. Bartholomaeus Anglicus, a 13th-century scholar, noted that "The North winde . . . purgeth and cleanseth raine, and driveth away clowdes and mistes, and bringeth in cleereness and faire wether; and againward, for the South winde is hot

BUFFETED BY BREEZES
A caped stroller loses his hat and his composure as he struggles into the wind in this 19th-century caricature entitled "March Wind". Meteorologically, the traditionally brisk winds of March are explained by exaggerated temperature differences that exist between the north polar region and the equator about the time of the vernal equinox, during the early spring.

& moyst, it doth the contrary deedes: for it maketh the aire thicke and troubly, & breedeth darknesse".

Today the methods of linking wind and weather are somewhat more complicated. Forecasters want to know first what the barometer is doing, and only then which way the wind is blowing. Once these facts are in hand, however, their matter-of-fact prose bears out the findings of the ancients. "When the wind sets in from points between south and southeast and the barometer falls steadily," reads the U.S. Weather Bureau's *Weather Forecasting* ("a storm is approaching from the west or northwest, and its center will pass near or north of the observer within 12 to 24 hours, with the wind shifting to northwest by way of south and southwest. . . ."

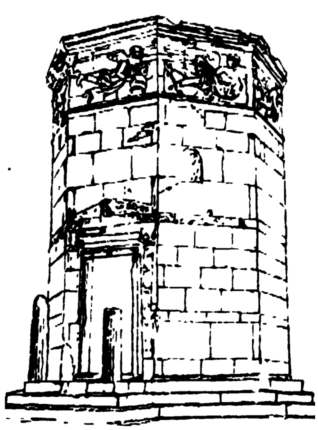
Shuttlecocks and cloud shadows

The wind's usefulness as an aid to weather forecasting led men to devise all sorts of systems and gadgets for studying it. Primitive weathermen of China and Egypt built wind vanes that showed the directions from which the wind was blowing. In 17th-century Europe, in the earliest days of modern meteorology, scientists measured the speed and force of wind by setting feathers adrift in it and watching their passage between two points. Or they measured the speed at which the wind blew a feathered cork disc along a wire. Sometimes they clocked the velocity of cloud shadows across a stretch of water or an open field.

In the 1760's, in Danzig, Michael Christoph Hanov tried to standardize wind-force measurements by raising flags of various lengths and noting at a given moment which one the wind lifted to a horizontal position. Hanov also experimented with a single flag loaded with varying weights; he based one of his wind-force tables on still another scale the degree of movement of a length of lead-weighted horse hair.

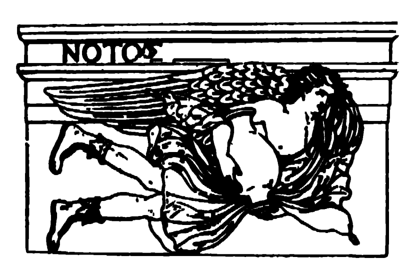
By the mid-19th century scientists were measuring the velocity of the wind by noting the rate at which it evaporated or cooled water. And one experimenter- presumably with perfect pitch—even used a device resembling wind chimes, rating the wind's speed according to the musical sounds it produced. About the same period, science hit upon the instrument that, in improved form, is still widely used today to measure wind velocity: the cup anemometer. A modern anemometer consists of three or four cups mounted at the end of horizontal arms that extend at right angles from a vertical shaft. The wind catches the cups, spins them round and rotates the shaft. The shaft is geared to a device that, like the speedometer of a car, registers the rate of revolution in terms of miles per hour.

But the complicated methods of modern forecasting require vast amounts of information- far more than the ground-level data that wind



AN EARLY OBSERVATORY, this Athaenian "Tower of the Winds" dates to the first century B C On its eight faces are carved figures representing the eight winds recognized by Aristotle three centuries earlier, four of which are reproduced at the right Aristotle seems to have anticipated modern ideas of polar fronts as determinants of weather: he divided winds into two classes, polar and equatorial, and described with amazing accuracy the weather likely to be brought by each

BOREAS, OR NORTH WIND



NOTOS, OR SOUTH WIND

vanes and anemometers supply. In the Western Hemisphere alone, 145 U.S. Weather Bureau stations send up more than 600,000 balloons a year to gather information on the upper atmosphere. At least 120,000 of them are sounding balloons, from each of which dangles a tiny electronic device called a radiosonde (*sonde* is French for "sounding line"). The radiosonde combines meteorological sensing equipment with a radio transmitter. As the balloon drifts aloft, rising at about 1,000 feet a minute, it sends back continuous reports on temperature, pressure and humidity until it rises to somewhere between 75,000 and 125,000 feet—at which altitude it bursts. Sometimes, additional information is supplied by electronic direction-finders on the ground, which gather data on wind speed and direction by following the same balloon's path and speed by radar.

Weather balloons sometimes carry aloft special metal-foil reflectors that are tracked by ground-based radar. These balloons are called rawinsondes (rawin is an acronym for *ra*dar and *wind*). On clear days ground observers watch the course of bright-coloured pilot-balloons, tracking wind speed and direction visually. Also, the Weather Bureau, NASA, the Department of Defense and the Air Force, all use rockets of various kinds to collect weather data. Some eject chemicals and bundles of metal strips, which are tracked by camera and radar; others are equipped with grenades that explode in the upper air, generating sound waves that yield data on high-altitude winds.

These investigations and others like them—made possible primarily as a result of the technological developments since World War II—have confirmed some heretofore unprovable theories, answered some once-unanswerable questions and settled some old arguments. They have also cast doubt upon some long-accepted points of view, a few of them quite basic. Nevertheless, much is known about the winds—how they are formed, and how and why they blow.

To begin with, winds are grouped into three categories: local and regional persistent winds; global persistent wind. and maverick, or episodic, winds, like cyclones and anticyclones, tornadoes and hurricanes.

Winds of sea and land, hill and valley

Local, persistent winds are almost invariably small-scale convection winds—the sea breeze and the land breeze, the mountain wind and the valley wind. Because they are comparatively shallow in depth and limited in range, they are simple winds. They blow from high-pressure area to low-pressure area, practically unaffected by such complicating factors as the rotation of the earth.

The sea breeze and the land breeze are caused by the difference in the temperature of the air over the land and water. During the day, the sun warms the land, and the land warms the air above it. The air rises—

APELIOTES, OR EAST WIND

ZEPHYROS, OR WEST WIND

and cool, heavier air flows in off the sea to take its place. During the night, the process is reversed: the sea, retaining much of its daytime warmth, warms the air over it—which rises and is replaced by heavier, cooler air blowing off the land.

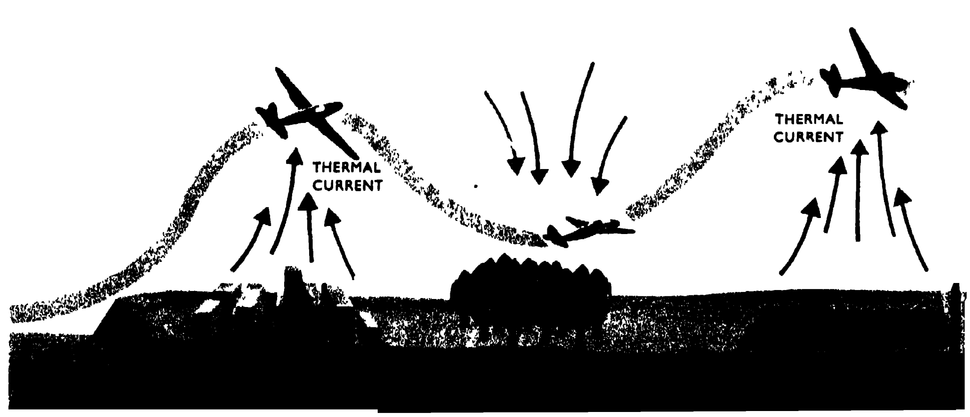
The sea breeze and its nocturnal opposite appear with virtually clock-like regularity along the coastlines of the tropics and subtropics. It is an old, dependable and blessed friend, bearing picturesque, poetic names: the *virazón* of Chile, the *datoo* of Gibraltar, the *imbat* of Morocco, the *ponente* of Italy, the *kapalilua* of Hawaii, the "doctor" of various English-speaking tropical and semitropical regions. Further north, the sea breeze tends to be seasonal, appearing in the warmer weather of late spring and summer, especially during June and July. The seasonal sea breeze habitually springs up between 10 and 11 o'clock in the morning, and starts to subside at about 2 o'clock in the afternoon. By 7 or 8 o'clock at night it has died out altogether. Then the land breeze begins to freshen, and the time sequence is repeated.

The hotter the climate, the faster and farther these breezes move, and the greater their mass. They always reach their maximum speed at the hottest time of day. In the temperate zones this top speed is a mild 8 to 12 miles per hour; in the tropics it is a brisk 20 to 24 miles per hour. Their inland range in temperate zones is a mere 9 or 10 miles, and their ceiling averages about 600 to 700 feet. But in the tropics the sea breeze extends 100 miles inland, and can have a ceiling of 4,000 feet or more.

Mountains as wind-makers

Mountain dwellers the world over are familiar with small-scale convection winds of a similar nature. Meteorologists call them thermal slope winds. They consist of air that blows upwards (from valley floor to mountain ridge) during the warm daylight hours, and downwards (off the ridges to the valley floor) during the cool hours of night. In the daytime the rocky mountain sides heat up quickly and generate rising currents of air. It is considerably warmer than the air at the same altitude over the valley. The cooler, heavier air over the valley presses down, and in effect squeezes the air up the slopes—where it becomes heated and joins the circulation system. Soon after sunset, the mountain side cools swiftly—much more swiftly than the valley. Then warm air rises vertically over the valley, while heavier cold air flows down the slopes and the circulation system is reversed.

In long, deep valleys—like those of the High Sierras or Alps—the valley wind, in addition to travelling up the sloping sides of the mountains, also flows up the long axis of the valley, from its wide to its narrow end. Frequently hot and unremitting, it raises choking clouds of dust from



RIDING THE WARM AIR, a glider traversing open country uses the natural vertical motion of thermal or convective currents to remain in flight. The steep slope of air thrown up by a coastal ridge (*left*) enables the glider to gain altitude Warm air rising over a city boosts it higher. It then dips towards earth in the downdraught of cooler air above a forest, soars again in thermal updraughts over a ploughed field, and finally descends in the downdraught over a pond. Meanwhile a second glider (*right*) is descending from a great height in the layered waves that form in the lee of a mountain range.

the valley floor and blows so steadily, year in and year out, that it deforms trees in its path. It denudes them of branches on the windward side, and twists their leeward branches into frozen free-form shapes. After sunset this valley wind subsides, and is replaced by a cooler, lighter breeze from the slopes and peaks at the valley's ends.

All over the world there are persistent small-scale winds that derive their unique character from local topography—the so-called orographic winds. One kind of orographic wind is the trans-mountain wind—like the *chinook*, the *Föhn*, and the *zonda*, all of which will be described later. Trans-mountain winds lose their moisture as they ascend the mountain barrier, then blow warm and parching down the leeward slopes into the valley beyond. Another common orographic wind is the bora, frequently referred to as a fall wind or drainage wind, because it is a wide, massive river of air that falls or drains from high, cold plateau country on to a warm plain or coastal region.

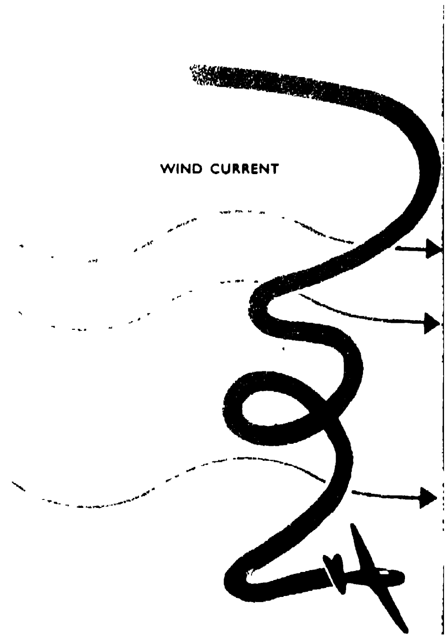
Unlike the warm trans-mountain winds, the bora blows across the land cold and furious, under bitter-bright and sunny skies. It is named after the most celebrated local wind of its type, the bora that howls down out of the Balkans and at times all but paralyses the Adriatic littoral from Trieste to the border of Albania. The prototype bora begins in Russia, crosses the high Hungarian plains, then the north-south ridge of the Julian and Dinaric Alps. Beyond the Alps, it falls down the mountains' seaward slopes to the Dalmatian plain, then blows out across the Adriatic Sea, where it whips up waves, atomizing their crests into a spindrift mist that Italian mariners call *fumarea*.

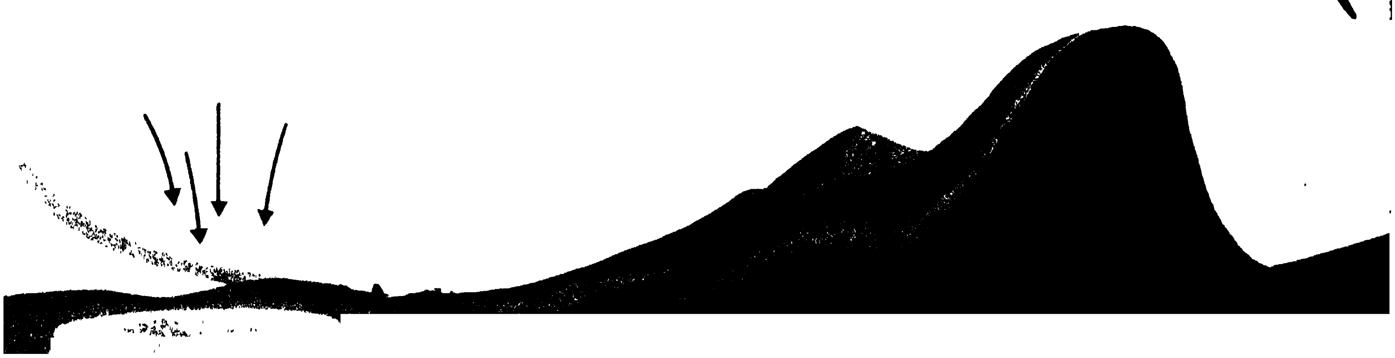
The wind that overturns rocks

The famous French mistral is a bora-like wind that drains off the plateau of central France. Cold, dry, bleak and relentless, it blows south from Burgundy in the spring and autumn, funnels down the narrow corridor of the Rhone Valley, then sweeps across Provence to the Gulf of Lions. "An impetuous and terrible wind", wrote the Greek geographer Strabo in the first century A.D., "which displaces rocks, hurls men from their chariots, crushes their limbs, and strips them of their clothes and arms. . . ."

Two thousand years have failed to mellow the mistral. To this day, it can still blow a man off a horse, upset a cart-load of hay and shatter windows with a blast of pebbles. In Arles, the mistral once nudged loose a string of engineless freight cars and blew them 25 miles to Port-St.-Louis before train-men could board them and brake them to a stop.

But the most dramatic—and historic—of the regional, persistent winds is the monsoon, a word derived from the Arabic *mausim*, or "season". It was first applied to the seasonal winds of the Arabian Sea that blow





six months from the north-east, then reverse and blow just as steadily six months from the south-west. The monsoon has always played an important role in the economy of the Middle and Far East. It blew the frail craft of the first adventurous traders from the east coast of Africa across the Indian Ocean to the rich Malabar Coast of India. And in the first century A.D., Arabian mariners, trimming their sails to it, fared safely north-east across the Gulf of Aden to the mouth of the river Indus. Three centuries later, they rode the steady monsoon winds all the way to China. Even today, India's economy is at the mercy of the monsoon. The country's huge rice crop, the staple food for its teeming millions, depends on moisture that the monsoon brings from the Indian Ocean.

A vast sea breeze

In simplest terms, the monsoon is a sea and land breeze, in capital letters. Instead of being limited to narrow strips of coastline, it sweeps to and fro over hundreds of thousands of square miles of land and sea. And instead of being set to the rhythm of day and night, it is keyed to the cycle of summer and winter. The land heats in summer and cools in winter, but the temperature of adjacent ocean areas remains relatively constant. As a result, massive convective updraughts rise over the land in summer, and air travels inland off the ocean to take its place—creating the long, moisture-laden summer monsoon. During the winter, when the continents are cooler than the oceans, the process is reversed.

Monsoon-like winds exist in many parts of the world, but the best defined monsoons are two Asiatic systems divided by the Himalayas. One is the East Asia monsoon, the predominant wind of Japan and mainland China. The other is the South Asia monsoon, powered by heating and cooling of the great Indian peninsula jutting into the Indian Ocean.

Mechanically, the trade winds that blow over the great ocean areas of the tropics and subtropics are like the monsoons. They are large-scale convection winds that blow predictably and persistently. But the range of the trade winds is global rather than regional, and they blow always in the same direction. They are planetary wind systems, and they form part of what meteorologists call the "general circulation" of the atmosphere—the three great bands of wind that blow around the earth in the Northern and Southern Hemispheres.

Like all convective systems, the general circulation is powered by an imbalance in temperature—in this case a difference between the temperatures at the two poles and the equator. Warm equatorial air rises and flows generally polewards, cold polar air sinks and flows generally towards the equator. But several factors complicate this simple concept of two hemispheric loops, or "conveyor belts", of moving air. One is the drag of the air against the earth's surface, the other is the rotation of the

earth itself. Together, friction and rotation combine to throw the general circulation into an enormous, swirling concatenation of currents.

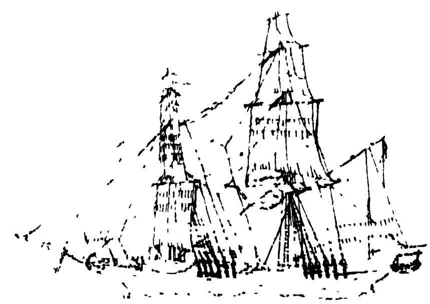
In tracing the course of these currents the logical place to begin is at the equator. A theoretical line called the heat equator girdles the earth through its hottest points. On both sides of this shifting line lies the region known since sailing-ship days as the doldrums, but which meteorologists call the "inter-tropical convergence zone". The air over the doldrums has very little horizontal movement—the sun's blazing heat lifts it almost straight up. This rising air branches outwards like a fountain, some of it turning north, some of it south, to form the upper-level air currents known as the anti-trade winds. As they reach 25° latitude, north and south, the anti-trades also divide. One stream, continuing towarus the poles, forms the upper level of the winds known as the westerlies. The other begins to descend back to earth, where it piles up in the region of the 30th parallel, creating a fair-weather zone of calm air. Sailors call this zone the "horse latitudes", perhaps because of the horses that died and had to be thrown overboard when Spanish ships heading for the Indies were becalmed here for weeks at a time.

When the descending air of the horse latitudes reaches the earth, it too divides, one stream returning to the equator, the other heading towards the poles. The equatorial current forms the famous trade winds—the mild, gentle winds that blew Columbus to America, the steadiest, most persistent winds on earth. This, indeed, is how they earned their name. "Trade" is an ancient word for track or path, and to "blow trade" is to blow steadily and incessantly in the same direction, along the same track. The trade winds replace the air rising over the doldrums, thus completing the equatorial convection system—a system generally referred to by meteorologists as the "Hadley cell", after George Hadley, who first suggested its existence in the 18th century.

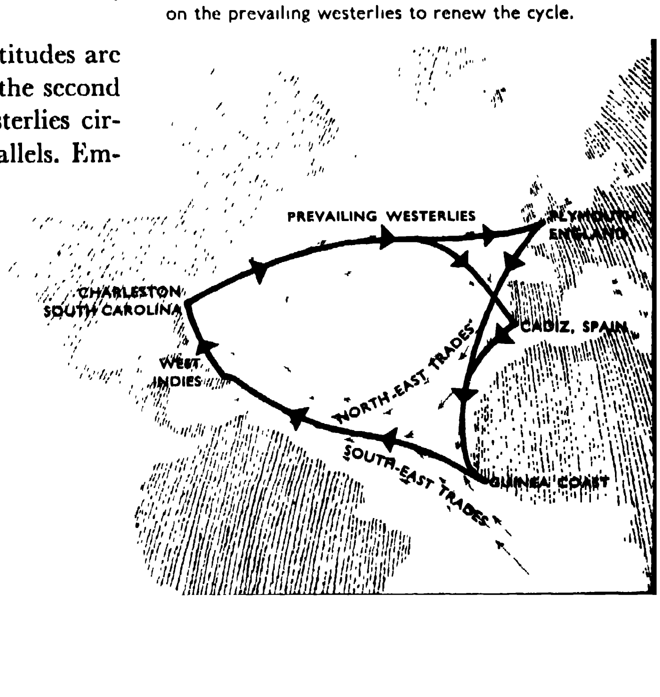
The effect of the spinning earth

If the earth were stationary, the trade winds would blow directly from north to south in the Northern Hemisphere, and the opposite way in the Southern Hemisphere. But the spin of the earth, west to east, deflects or steers the trades—and in fact all winds of the general circulation—making them veer off their strictly north-south course. This effect is called the Coriolis force (although it is not, strictly speaking, a real force at all). It takes its name from the 19th-century French mathematician, Gaspard Gustave de Coriolis, who first described it.

The air currents moving towards the poles from the horse latitudes are deflected eastwards and merge into the prevailing westerlies—the second of the great wind systems of the general circulation. The westerlies circle the earth in waving skeins between the 30th and 60th parallels. Em-



ABETTING SLAVERY, the trade winds and the prevailing westerlies, indicated on the map below by coloured arrows, helped to make the traffic in Negroes possible from the 16th to the late 19th century. A ship such as the one shown above voyaged on the north-east trades from Europe to Africa with goods to be exchanged for slaves. Loaded with human cargo, she would ride the trade winds to the Americas, there to barter slaves for sugar, rum or cotton. Then she would return to Europe on the prevailing westerlies to renew the cycle.



bedded in their main currents, roughly six miles out, are the jet streams that, blowing at an average of 200 to 300 miles an hour, push east-bound airliners across the American continent two hours faster than they can make the same flight in the opposite direction.

The wildest winds

Even at ground level the westerlies can be the wildest of all the persistent winds. In the Southern Hemisphere they rush unimpeded, at gale force, across thousands of miles of open water, driving before them scudding storm clouds and rolling the sea into mountainous waves 60 feet high. Awestruck sailors encounter them most frequently in the latitudes between 40° and 50° south, and call the region the "roaring forties". But as they near the poles, the westerlies lose their speed and force—much as the water at the banks of a stream loses its forward motion and drifts into eddying backwaters. At the 60th parallel they brush against the last of the bands of winds that make up the general circulation—the polar easterlies.

The polar easterlies begin as masses of cold air bred by conditions on the earth's surface. Just as there is a heat equator circling the earth through its hottest points, coinciding roughly with the geographical equator, so there are poles of intense cold in the vicinity of the geographical North and South Poles. In the Northern Hemisphere one of these poles of cold is in Siberia, and includes the two towns of Verkhoyansk and Oymyakon, where temperatures have reportedly reached −68° C. Another lies in north-western Canada, where the town of Snag has reported a low of −63° C. A third cold pole in the Northern Hemisphere is in Greenland. In the Southern Hemisphere the great pole of cold is on the continent of Antarctica, where a Soviet weather station, Vostok, has registered a temperature of −88.3° C. These poles of cold breed far-spreading mantles of heavy, frigid air that fan out and move towards the equator, are deflected by the Coriolis force, and are the polar easterlies.

Most of the northern temperate zone's changeable weather originates along the undulating line where the polar easterlies and prevailing westerlies meet. The clash of the two currents, with their different temperatures and humidities, creates a more or less permanent condition of atmospheric instability and perturbation; great eddies and vortices form sporadically, to move off as isolated masses of whirling wind within the general circulation. Unlike the general circulation, however, these wind systems rise and subside, are born and die—in short, are episodic. To meteorologists they are known as cyclones and anticyclones, and one is a mirror image of the other. Cyclonic wind systems spin around a centre of low pressure and converge upon that centre, rotating counter-clockwise in the Northern Hemisphere, clockwise in

the Southern Hemisphere. Anticyclonic winds rotate in the reverse direction, around a high-pressure centre, and flare out from the centre. But both systems are alike in one respect: they cover areas of hundreds of thousands of square miles.

Cyclones are the familiar "lows" of the weather map, the bringers of bad weather—clouds, rainstorms, blizzards. But they are not synonymous with the violent wind-storms so often and mistakenly associated with their name: tornadoes are not cyclones. Anticyclones are the weather map's "highs", and normally bring good weather. Together, highs and lows account for the temperate zone's variable day-to-day weather. Moving around the earth west to east, in endless and erratic procession, they bring clear skies and searing droughts, gentle rains and tempestuous 50-mile-an-hour gales.

In the tropics a low can grow into the churning aerial maelstrom of a typhoon or hurricane—two names for the same kind of storm. Both are born over warm tropical seas, where the air is laden with moisture and heavily charged with latent heat energy. Their breeding grounds exist in half a dozen places around the world—in the northern Atlantic and Pacific Oceans, the Indian Ocean, the China and Arabian Seas. The hurricane, from *huracan*, the West Indian god of storms, sweeps in from the Atlantic about 10 times a year, roughly between the months of May and September. The typhoon, which generally makes its appearance in August and September but can occur in any season, blows up on an average 20 times a year in the North Pacific alone. During their violent lives (described in detail in the picture essay preceding this chapter) these tropical storms do incredible damage.

Most vicious and capricious of all storms, however, is the tornado, a travelling whirlwind whose name comes from the Spanish *tronada*, thunderstorm.

The twisters of the U.S.

Tornadoes occur in many parts of the world, but nowhere do they occur more frequently and with greater violence than in the United States, where each year 500 to 600 of them rip their way across the countryside. Most of them occur during the afternoon, shortly after the passing of the day's highest heat, and they are always associated with thunderstorms. Green lightning flickers weirdly over the land, and dark clouds glow strangely green and yellow. They are accompanied by a sullen, remote rumble which sounds at close range like the roar of a thousand express trains travelling at top speed.

The average tornado has a central core perhaps 250 yards in diameter and may travel along the ground only 100 feet, but can go 100 miles. It usually appears as a funnel-shaped cloud, but sometimes it is a relatively

THE WRATH OF A HURRICANE was dramatically evoked in the 18th century by an officer of the frigate H.M.S. *Egmont*, who sketched her wallowing helplessly in the Caribbean during the Great Hurricane of 1780. This storm, which was reported to London (*below*) by the governor of Jamaica, was only one of hundreds to hit the West Indies. But it was one of the worst: more than 9,000 persons were killed on Martinique alone.

A

GENERAL ACCOUNT, &c.

SECTION I.

ACCOUNTS FROM JAMAICA.

Copy of a Letter from Major General Dalling, Governor of the Iſland of Jamaica, to Lord George Germain, one of his Majeſty's Principal Secretaries of State, received by his Majeſty's Sloop Alert, Captain Vaſhon, and publiſhed in the London Gazette, Jan. 12, 1781.

My Lord, *Jamaica, Oct. 20, 1780.*

I AM ſorry to be under the diſagreeable neceſſity of informing your Lordſhip of one of the moſt dreadful calamities that has happened to this colony within the memory of the oldeſt inhabitant.

On Monday the 2d inſtant, the weather being very cloſe, the ſky on a ſudden became very much overcaſt, and an uncommon elevation of the ſea immediately followed. Whilſt the unhappy ſettlers at Savanna la Mar were obſerving this extraordinary

straight-sided cylinder, a thin, curiously twisted rope or an elephant's trunk swinging across the eerily lit countryside.

As the tornado advances it scoops up and spews out timbers, trees, livestock, rocks, refrigerators, roof-tops, cars, chickens. Even people have been carried aloft by tornadoes. In Texas, in 1947, two men were carried 200 feet by a tornado and were then set down virtually uninjured. During another tornado, a man and wife in Ponca City, Oklahoma, were inside their house when it was blown away; its walls and roof exploded, but the floor remained intact and eventually glided back to earth, depositing the couple unharmed.

The top speed of a tornado's whirlwind has never been measured; the instruments never survive. Meteorologists think it probably reaches about 400 miles an hour, and may go as high as 600 or 700 miles an hour—approaching the speed of sound. In its wake it leaves some weird testimony to its power. One tornado in 1925 drove a large plank into the trunk of a tree, wedging it firmly enough to support the weight of a man on its free end. And tornadoes regularly denude chickens of their feathers—usually, but not always, doing in the chickens as well. Terrifying and unforgettable—and intrinsically baffling—the tornado is the briefest but most intense of all the many kinds of winds that swirl in endless convolutions above the surface of the earth.

Great Rivers of Air

Tempest, zephyr, gale, breeze, squall—these are but a few of the thousand names for wind. And though man has used and been abused by winds for the 60,000 years of his existence, it has been only within this century that he has even begun to understand their behaviour. Winds are the atmosphere in motion. They start to blow when warm air, expanding, is forced up, and cooled air, contracting, sinks. From this simple beginning the behaviour of the winds grows almost inconceivably complex. Tropical air heads towards the poles, polar air towards the equator. The spinning of the earth makes the winds swerve, and the earth's pock-marked, irregular surface—not to mention the changing temperatures of its oceans and continents—exerts a further profound influence. Despite all this, the global winds are not chaotic. Instead, they move in stately, measured patterns, within which the most violent hurricane is little more than a momentary eddy.

FULL SAIL BEFORE THE WIND

Spinnaker bellying and trade winds aft, the 75-foot schooner *Constellation* makes good time towards Honolulu to win in its class in the 1959 trans-Pacific race from Los Angeles. The 2,225-mile voyage took the *Constellation* 10 days, 23 hours. Speed in such races depends largely upon expert knowledge and the utmost use of the prevailing winds that are found in tropical latitudes.

CIRCULATION'S BOLD DESIGN
Dyed water illustrates a basic process governing air circulation. The blue water, cooled by a pipe (*right*), sinks and flows left along the bottom of the tank. Red dye, which is dropped into warmer water, first sinks of its own weight, then slowly rises to flow along the surface.

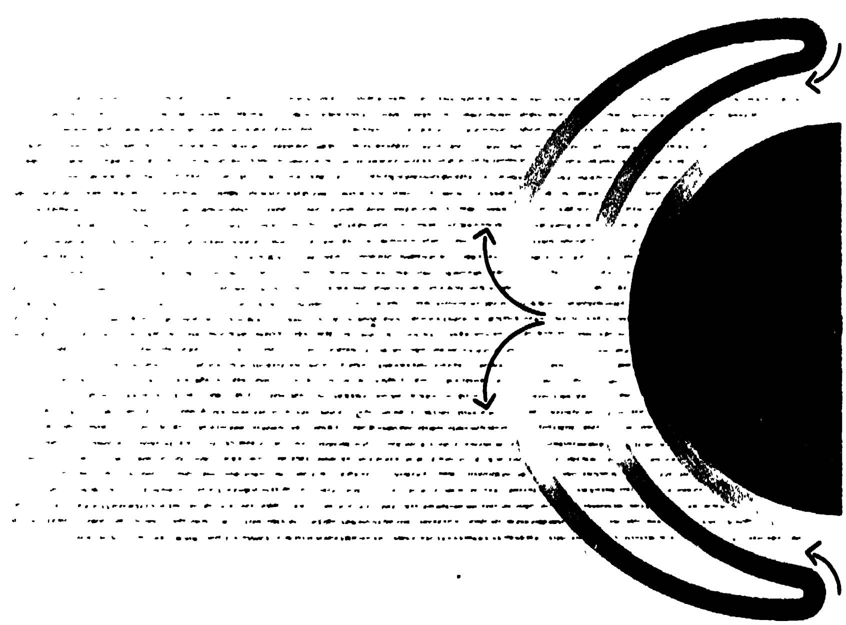
Circuits That Distribute Heat

The global movement of winds can be visualized in simplified form as a series of rotating cells, or belts (*opposite*), propelled by differences in their temperatures. On either side of the equator, hot tropical air rises, spills outwards, cools somewhat, and then sinks earthwards in the vicinity of the 30th parallel of latitude. Similarly, at the poles, cold air sinks, gathers warmth, then rises again to repeat the cycle. Between each set of these thermally generated cells is a middle-latitude cell. The wind circulation in this cell, caught between the upward thrust of the polar cell on the one side and the downward pull of tropic air on the other, operates in reverse, as if it were part of a gear train. Contrary to the normal thermal movement, its warm air sinks and its cold air rises.

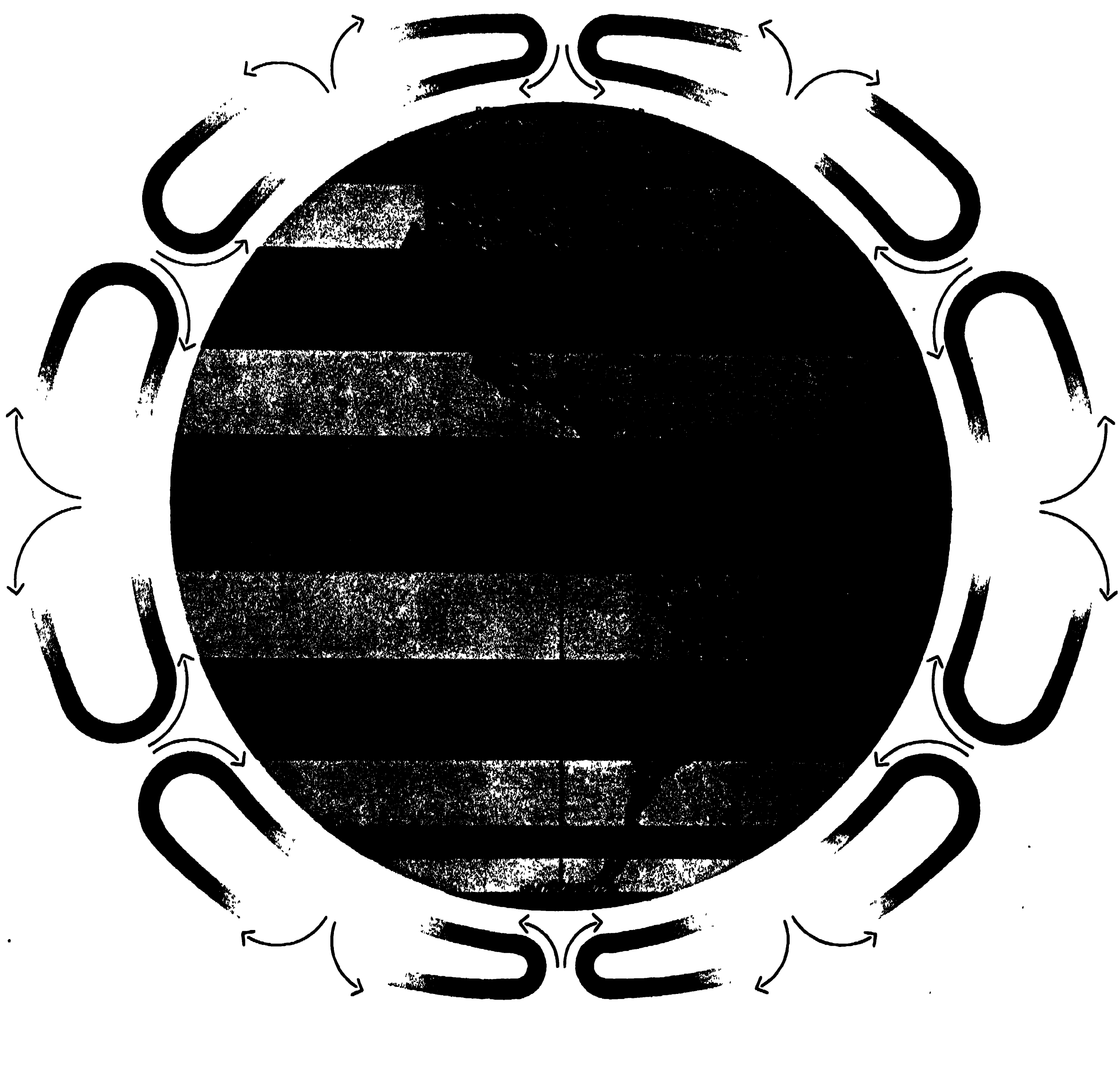
The total effect is as if a gigantic conveyor belt were employed in the transfer of heat away from the tropics and towards the poles. Thus a portion of the heat from each tropic cell is passed on to the mid-latitude cell; when these warmed winds reach a latitude of about 60°, they join with the rising currents of the polar cells, to which they pass along a measure of their heat.

The process is much less simple in actual operation than in the diagram: many other influences also act on the winds, turning and churning them as shown on the pages that follow.

WINDS ON A FEATURELESS EARTH
Atmospheric circulation is shown below as it would occur if it were not affected by the earth's spin, tilt or topography. In this hypothetical situation, air warmed in the tropics is forced up and spreads north or south, eventually reaching the poles. Cold air from the poles flows at lower altitudes back towards the equator. If such simple circumstances actually existed, air circulation for the entire globe would follow a fixed pattern, involving two huge wind cells moving in much the same manner as the water shown in the tank at the left above. Each day's weather would be the same, with the entire earth under the influence of gentle equator-bound winds



A GLOBAL GEAR TRAIN OPERATED BY THE TRANSFER OF HEAT



BELTS OF PRESSURE

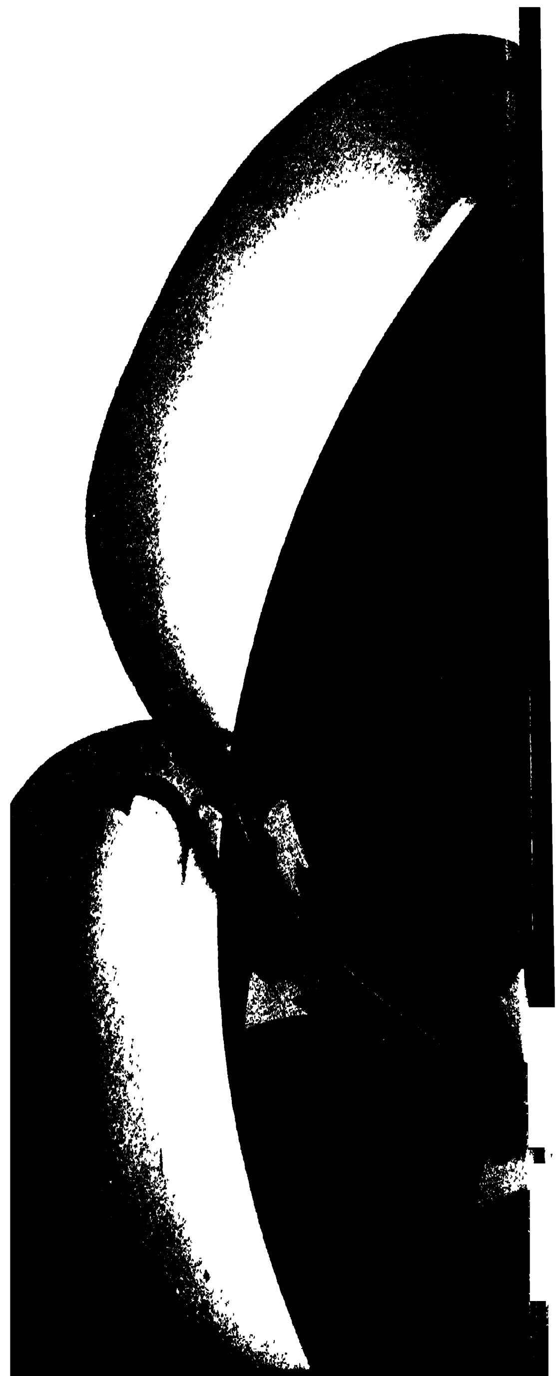
Heat is airlifted and passed along from the tropics to the poles by this system of wind cells. In the process, some general patterns of weather evolve. Where air currents have a tendency to flow downwards, as at the poles, high-pressure areas are fairly constant. Where air circulation is upward—for example, at 60° latitude—a predictable band of low pressure occurs. Again, descending air at the junction of the mid-latitude and tropic belts creates the zone of high pressure and light winds which for centuries has been colloquially known as the horse latitudes. Rising tropic air near the equator accounts for the low-pressure area called the doldrums. Here, because the movement of the air is generally vertical, the equatorial seas are calm —disturbed only occasionally by fitful winds that do not blow for long in any one direction.

STRAIGHT LINES BENT BY SPIN
The Coriolis effect can be demonstrated using a gramophone turn-table (of the free-turning variety), a cardboard disc with a map of the Northern Hemisphere, and a pencil and ruler.

The Curving Coriolis Effect

In the 19th century, G. G. Coriolis, a French mathematician, observed that an object moving across a turning surface veers to the right or left, depending on the direction of rotation. Thus, as the earth spins towards the east all moving objects in the Northern Hemisphere tend to veer to the right, and in the Southern Hemisphere to the left. A jet plane flying to New York from Seattle would, if this so-called Coriolis effect were not compensated for, land in South America as the earth spun under it. The winds are also deflected by this rotation. Instead of blowing due north or south, they become prevailing easterlies and westerlies (*right*).

SWERVING CURRENTS OF WIND
This simplified drawing shows the global circulation of the winds. The orderly north-south circulation produced by the rotating cells is distorted by the earth's rotation into diagonally blowing winds (*red arrows*). As shown in the diagram, this would still leave a systematic appearance—but local topographical features break this up into millions of unshown eddies.



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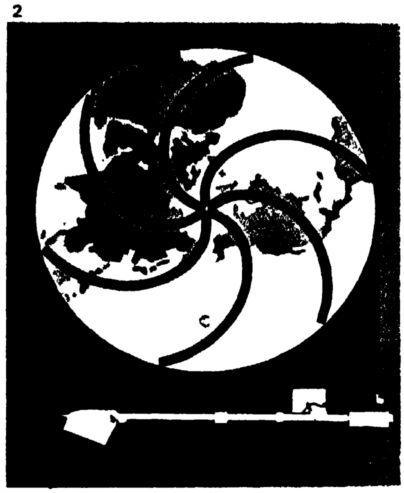

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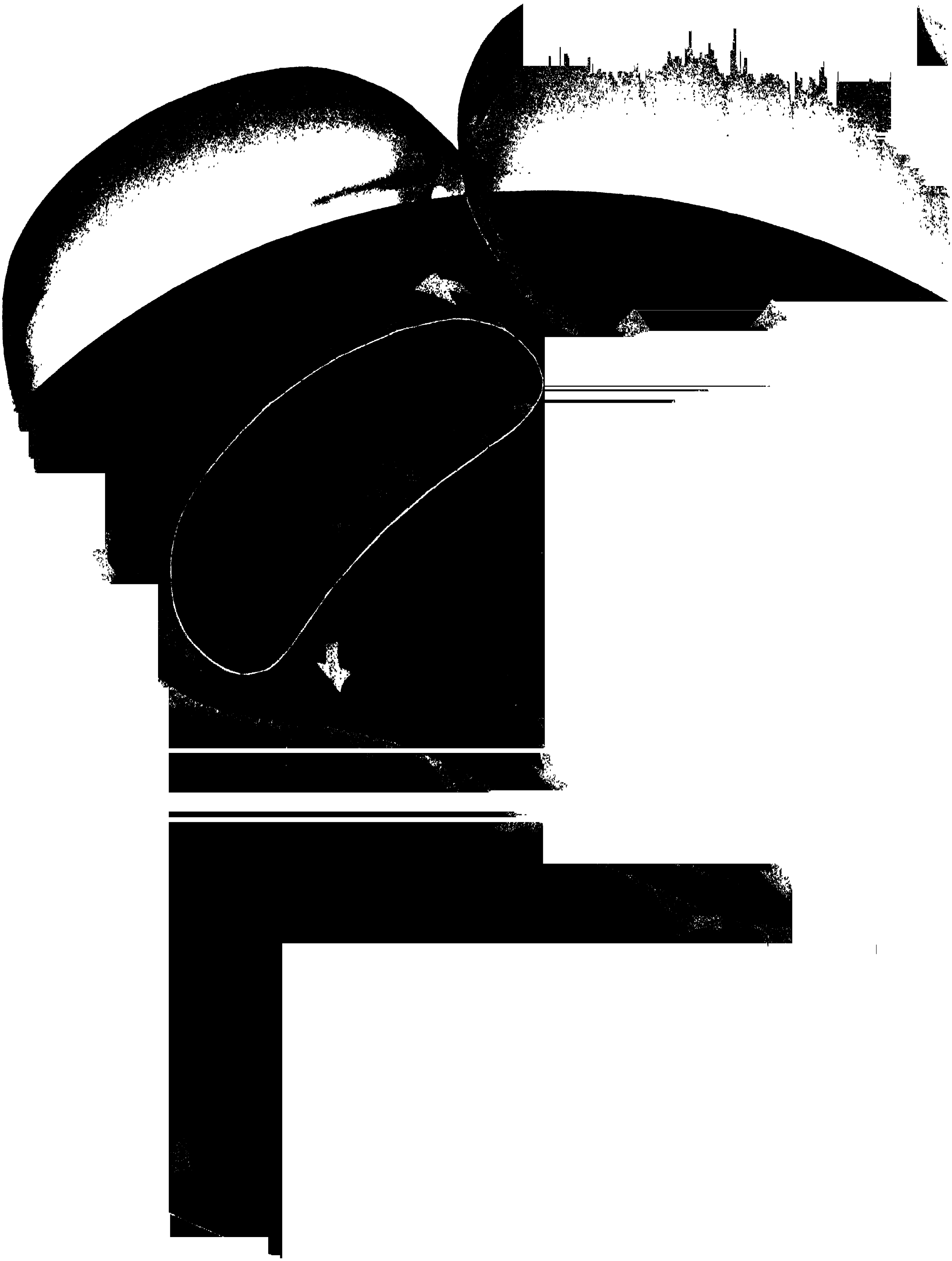
(1) With the North Pole placed over the spindle, the turn-table is spun counter-clockwise, which is the direction of the earth's spin in the Northern Hemisphere. A line drawn along the straight edge of a stationary ruler describes an arc, owing to the fact that the turn-table is moving.

(2) When a series of lines is drawn from the pole (the spindle) to the equator (at the rim), they all curve to the right, or west. Thus the earth's rotation deflects the southerly trending winds of the tropic and polar air cells and bends them into a sweeping flow towards the west.

(3) The westward sweep of winds in the tropic and polar air cells is reversed in the middle-latitude cell (which is shown blank on the map). In this region the air movement is generally northward, with the result that the Coriolis effect bends these winds into an eastward flow.



As SURELY AS SPRING PRECEDES SUMMER, clouds precede the fall of water on the face of the earth. Although water is present in some degree almost everywhere in the atmosphere, it is usually unseen, in the form of vapour. Clouds are patches of the air's water content made visible, giving clues about the weather to come.

Man has always looked on clouds and their life-giving downpour of rain with awe, as part of the majesty of creation. Sometimes he has tried to influence them with religious ceremony and magic, but without much success. As the voice of Jehovah scornfully asked Job from the whirlwind, "Canst thou lift up thy voice to the clouds, that abundance of waters may cover thee?"

But if man still cannot control the formation of clouds and the fall of rain, except in the puniest way, he can at least watch them coming. Much of the pageantry of weather is the pageantry of clouds moving across the sky. Of the three main ingredients in a day's weather—heat, wind and water—water is the only one of the three that is actually visible even some of the time.

It was apparent to the earliest hunters, farmers and mariners that clouds were harbingers of weather. Cloud folklore is far too ancient to trace to its origins. A weather book written in the third century B.C. by Theophrastus, a pupil of Aristotle's, warned that certain clouds were sometimes signs of rain. The English language abounds in old adages concerning clouds and weather. For example, mountainous clouds in the morning were considered dependable signs of rain to come: "In the morning mountains/In the evening fountains".

But the men of past centuries could only conjecture at the reasons why raindrops, snow-flakes, sleet or hail fall from clouds. Plutarch observed that a big battle is often followed by rain, and the theory that warfare somehow causes rain has probably revived with every war since; it was still flourishing in the muddy trenches of World War I. Explanations have ranged from the belief that offended gods [illegible] to clean up carnage promptly through the theory that rain-stimulating vapours rise from the blood and sweat of soldiers to the suggestion that the waters are shaken from the clouds by the noise of cannon. In the early 1910's the cereal magnate C. W. Post tested this last theory by bombing clouds with dynamite over a period of years in Battle Creek, Michigan. Showers sometimes fell, but it usually rained elsewhere too, without benefit of bombs. On one occasion, while congratulating himself on his success, he was informed that it had rained that day from the Pacific Coast to the Great Lakes.

It was not until the 19th century that scientific light was first shed on clouds. The American meteorologist James P. Espy declared in 1830 that there was a connection between convection—the rising of warm air—and the condensation of atmospheric vapour. Later meteorologists began to

explore the exact physical processes involved in condensation and in precipitation—the fall of water from the sky to the ground. The processes proved harder to unravel than anyone had supposed.

Today meteorologists have more interest than ever in the problems posed by clouds. They believe that these ephemeral, airborne masses of microscopic water droplets will help them to find the way to their most important goals: more accurate forecasts, and eventual control or modification of the weather. They are spending more time, effort and money on the study of clouds and cloud physics than on any other aspect of meteorological research.

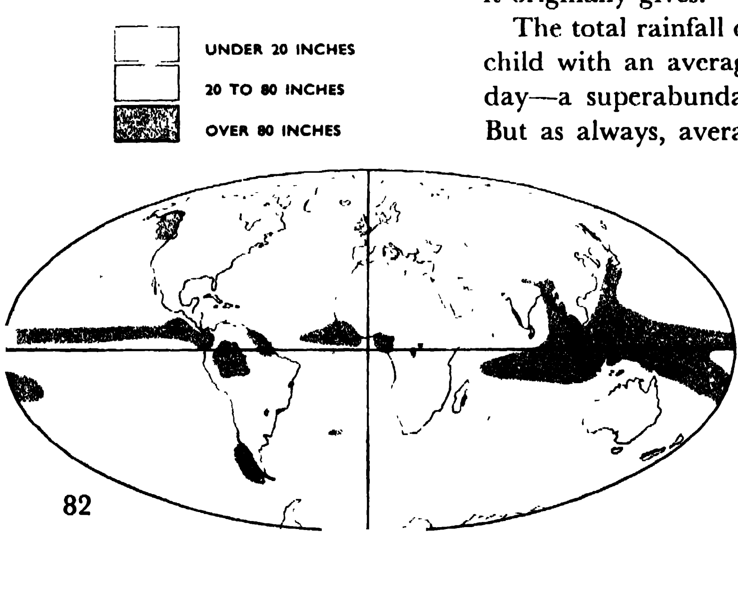
A new look at the clouds

For centuries all men ever had was an earth-bound view of clouds, but now the meteorologist's view of them is positively Jovian. Observers fly under, through and over them in aeroplanes, capture cloud droplets on glass slides filmed over with oil or soot—each droplet so minute that it takes a million of them to make a raindrop—and subject them to microscopic study. Balloons and light beams determine the altitude of clouds, and radar locates storm clouds too far away to see, plots their shape from top to bottom, and keeps track of their growth and movement.

In 1959 cloud-watching literally reached new heights when photographs of the earth's cloud cover were taken from a missile 700 miles out in space. For the first time, a global sweep of clouds was seen, reaching from Florida to the African coast, from the mouth of the Amazon to the North Atlantic. Since April 1960, Tiros weather satellites have relayed millions of informative pictures of cloud cover from heights of about 450 miles, making possible the global cloud maps that are now routine in weather analysis and forecasting.

Clouds are water in transition—a crucial stage in the earth's majestic hydrologic cycle, in which an estimated 95,000 cubic miles of water circulate between earth and sky each year. Of this total, some 80,000 cubic miles are evaporated off the oceans and 15,000 cubic miles from land—from lakes, rivers, moist earth and vegetation. The atmosphere carries this moisture about and eventually returns it to earth again as rain, snow, sleet or hail, or as frost or dew. The average annual rainfall around the world is an estimated 40 inches. About a quarter of it—an estimated 24,000 cubic miles—falls on land. Thus, luckily for humans, the waters of the earth are distributed and the land receives from the air more than it originally gives.

The total rainfall on land is enough to provide every man, woman and child with an average of about 20,000 gallons of pure rain-water every day—a superabundance even on an increasingly more crowded earth. But as always, averages are deceptive. Where the rainfall depends on



WORLD RAINFALL and its distribution, indicated by different-coloured areas in the map at the left, depend on patterns of wind and pressure. The low-pressure belt at the equator is an area of abundant moisture and heavy rain. Where mountains push the winds upwards, yearly rainfall also tends to be heavy. But continental interiors, cut off from the sea by mountains or distance, are usually dry.

geographical factors and global winds. The amount of rainfall varies from less than an inch a year in desert areas to the torrential annual average of 470 inches that pours down on Mount Waialeale in Hawaii, the rainiest spot on earth. In America, the spread ranges from a meagre 1.7 inches in California's Death Valley to a copious 140 to 150 inches in coastal areas of the Pacific North-West, only 800 miles away.

Most condensation—whether it is the appearance of a miniature breath-cloud on a winter's day or the formation of a towering summer thunderhead—results from the cooling of water vapour. Under normal atmospheric conditions, there is a simple relationship between temperature and the capacity of water to remain in a highly energetic, vaporous state. The higher the temperature of the vapour, the faster its molecules move. When the molecules are moving fast enough, many of them can cram into a given space without sticking to nearby solid objects or to one another; thus warm air can contain a great many vapour molecules. But if the air is cooled, the molecules slow down, and as they strike surfaces, bits of dust or other molecules, they tend to stick. The vapour begins to condense.

The amount of vapour present determines the temperature at which condensation occurs. If relatively few molecules of vapour are present, they are less apt to collide even at low temperatures. If the air is crowded with vapour molecules, they will condense at higher temperatures. The temperature at which a given amount of vapour in a body of air will condense is called its dew-point.

One other factor besides temperature and quantity of water influences atmospheric condensation. This is the presence of a surface or particle on which water can condense. In the absence of such objects, condensation is drastically slowed. In laboratory experiments, researchers have crammed astonishing amounts of vapour into a vacuum, or into carefully filtered air, before condensation began more than four times the amount that would begin to condense in the same volume of particle-filled air.

Landing fields for molecules

The surfaces that abound at earth level often act as cooling agents for the surrounding air. Large drops readily form on them without going through any intermediary cloud stage. Water molecules that touch the surfaces tend to stick—and once stuck they attract more molecules. In a familiar household example of this process, the vapour from a hot shower strikes a cool surface—such as the bathroom mirror—and coats it with beads of moisture. At night, in the same fashion, large drops of dew quickly gather on every cooling blade and leaf. In very cold weather, vapour may condense directly into ice crystals; frost coats the ground and covers window-panes with delicate patterns.

High above the ground, there are no such cooling surfaces. Neverthe-

less, the atmosphere swarms with tiny particles of foreign matter, around which water may condense. These "condensation nuclei" are present everywhere in varying amounts, from 100 per cubic inch far over the oceans to 65 million per cubic inch in polluted city air. Salt particles are probably the most numerous condensation nuclei. They are produced by the evaporation of sea spray and are distributed all over the world by global winds. The many fires that occur on earth also fill the air with chemical particles. They rise in the smoke from forest fires, factory chimneys, car exhausts and the like, and also serve as condensation nuclei. Dust, most of it from soil and rocks, constitutes a third large category. The effectiveness of these particles as condensation nuclei depends on their size and the capacity of water molecules to adhere to them, but as far as is known, every patch of air in the troposphere contains enough nuclei for vapour to condense at or near the normal dew point.

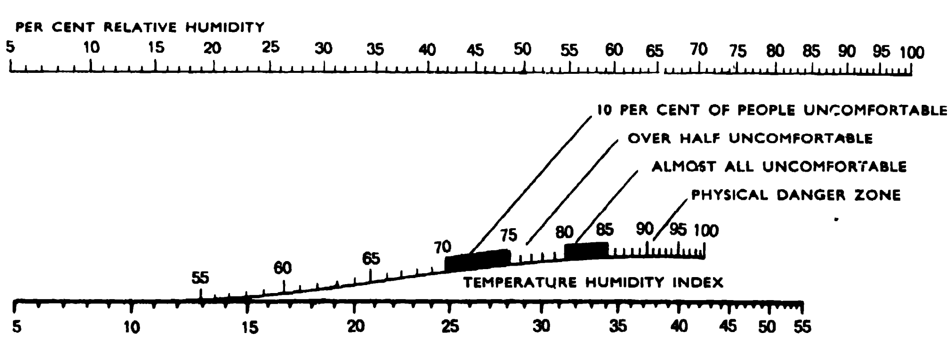
Earth-bound clouds

Humans can see this process at work in the formation of a fog—which is simply a cloud that occurs near the earth. Ground fogs often form in damp pockets at night—in river valleys, over streams and bottom-lands —after the earth has radiated away much of the daytime heat. Fog may also form when warm, damp air blows over the cool earth at night, or over the surface of the cool sea. In either case, damp air is chilled to its dew point. Molecules of water fasten on airborne nuclei floating nearby. The droplets so formed are quite different from dew-drops, as anyone can tell from the feel of them on the face, or the look of them as they float about. Thousands and thousands of millions of them swirl through the air, but they do not readily coalesce unless they strike a surface and stick. Thus in the midst of the fog, large drops march along a window-sill or spangle coat collars and hair.

The most familiar clouds, of course, appear high above the earth. They are formed when moist air is pushed upwards and cooled by the process of expansion. Its vapour content reaches the dew-point and begins to condense on surrounding nuclei. The tiny droplets, some as small as .0004 inch in diameter, fall very slowly, the air's resistance just balancing their small weight and buoyancy.

Clouds present ever-changing skyscapes of infinite variety and significance. To understand them and the weather they portend, it helps to know their names. The international classification system used by the World Meteorological Organization (WMO) is based on one devised in the early 19th century by an English chemist and Quaker, Luke Howard. Howard divided clouds into three fundamental classes, according to their appearance to ground observers: *cirrus* (Latin for "curl of hair"), *stratus* ("spread out") and *cumulus* ("pile").

A DISCOMFORT FORMULA for hot, humid weather is given in the chart below. Called the temperature-humidity index (*curved line*), the formula is based on the relationship between air temperature (*bottom line*) and relative humidity, which reflects the air's degree of saturation (*top line*). To determine the index, a line (*pencilled at centre*) is drawn between the temperature and humidity readings; the point at which it crosses the curved line determines the temperature-humidity index The higher the index reading, the more uncomfortable the average person will be.



Cirrus refers to high clouds, appearing from about 20,000 feet up. These atmospheric regions are so cold that cirrus clouds are composed of ice crystals rather than water droplets. Unlike clouds composed of liquid droplets, they are hazy in outline and delicate in appearance, resembling wisps of hair, or light feather strokes of zinc white from an artist's brush.

Stratus clouds come in layers or broad sheets, more or less uniform in contour and colour.

Cumulus clouds, sometimes called cauliflower clouds, are conspicuous for their vertical development. Their tops are usually dome-shaped, perhaps with billowy knobs, while their bases are flat, and they often travel sedately in flocks across the sky. Single cumulus clouds pile majestically upwards in towering castles and sky-mountains.

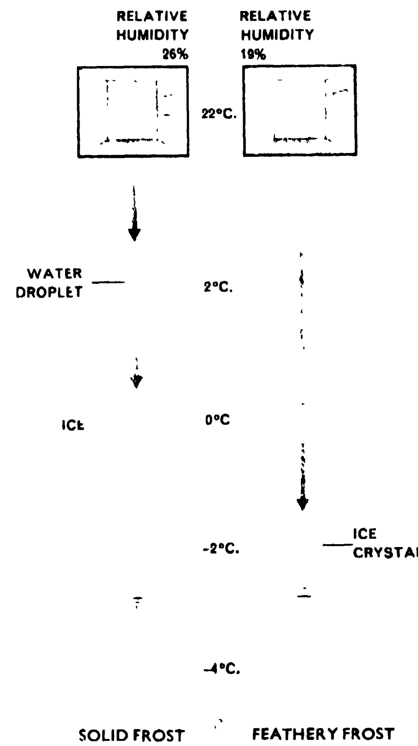
Although these are the main categories, clouds can rarely be pigeonholed into them neatly. Cloud-cataloguers have had to invent combined names to describe the many variations of cloud that actually occur. For example, rolling masses of grey and white clouds that cover large areas of the sky, particularly in winter, are called stratocumulus clouds. A high, spreading cover of cirrus may be called cirrostratus. The Latin word *nimbus* ("rain cloud") is often added to indicate that the cloud is precipitating: thus stratus clouds from which rain or snow is falling are called nimbo-stratus; dark, towering cumulus clouds, sometimes called thunderheads because they generate storms, are cumulo-nimbus.

The rising of moisture-laden air that results in the formation of clouds is caused by three things, operating singly or in combination: hills or mountains, a wedge of underlying cold air and, finally, heat, which generates an upward convection current.

The cloud-capped mountains

When air is lifted by sloping terrain, the increasing altitude causes it to expand and cool. The vapour it carries reaches its dew point, condenses on nuclei and turns into clouds. This process occasionally leads to unusual phenomena. A single mountain, like New Hampshire's Mount Washington, may be so high that it wears a cloud, called a cloud-cap, on its summit more or less permanently. Sometimes a range will regularly wring all the moisture out of the skies on its windward side, leaving the land to leeward parched; thus deserts lie at the foot of many of the eastern slopes of the Sierra Nevada. When hot, dry winds, such as the Rocky Mountain chinook, the Alpine *Föhn* or the Andean *zonda*, sweep down from the mountains across the land, it is sometimes possible to stand in the leeward valley and see the moisture draining away above. Seething masses of cumulus clouds loom behind the mountain tops; they have come to be called the *Föhn* wall.

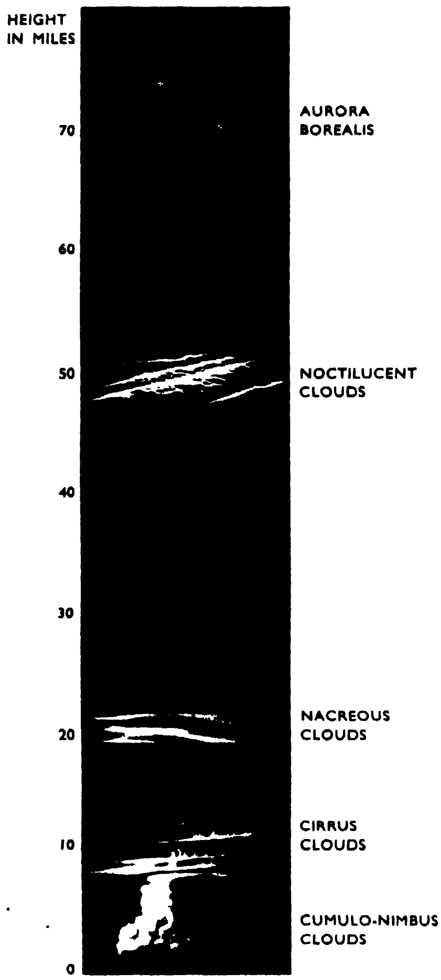
A second mechanism for lifting warm air is a moving wedge of cold air.



FROST PATTERNS on a window-pane are affected by the amount of moisture in the atmosphere. Two samples of air—one measuring a relative humidity of 26 per cent at 22° C. (*left*), the other a relative humidity of only 19 per cent (*right*)—are cooled. The moister air reaches its dew point at 2° C., at which point water vapour begins to condense into droplets. Further cooling starts these droplets freezing at 0° C. But for the drier air the temperature must drop below freezing before condensation begins. Then water vapour turns directly into crystals of ice. On window-panes (*bottom*) this difference causes varying patterns of frost—a flat sheet of ice on the left, and a feathery pattern of crystals on the right.

In the United States, dense polar air masses, arched like vast inverted bowls over perhaps a million square miles of territory, regularly move south from the North Pacific, Canada and the North Atlantic. Just as regularly, moist, light, tropical air masses travel north from the Pacific, the Gulf of Mexico and the Caribbean. U.S. weather maps are a daily chronicle of the meeting and mixing, waxing and waning of these masses.

When two contrasting air masses meet head on, the sloping boundary between them is called a front. When a tropical air mass displaces a polar air mass, the boundary is called a warm front; when cold air displaces a warm air mass, it is called a cold front. Each kind of front generates a characteristic sequence of weather. It is not necessary to have a weather map with fronts drawn on it to tell what is happening. It is possible to look up and read the drama of the clouds.



THE HIGHEST CLOUDS, seen only in the same polar or subpolar regions where auroras occur most frequently, are the noctilucent (literally "night-shining") clouds. Forming at a height of about 50 miles, noctilucent clouds get their name from the fact that they are visible only during the twilight hours Some meteorologists think these clouds consist of crystals of ice formed on tiny particles of dust from space Below the noctilucent clouds are shown nacreous ("mother-of-pearl") clouds—rare clouds of unknown origin, cirrus clouds, the highest of the ordinary clouds, and cumulo-nimbus, or thunder-heads.

The coming of a front

A city may be sitting comfortably in the middle of an inverted bowl of polar air which has brought a spell of fine summer weather—of clear blue skies and cool, dry air—when a mass of moisture-laden tropical air begins pushing north. The warm air rides up over the denser polar air somewhat like wind driving up a mountain slope. As it rises, it cools. As it cools, its water vapour condenses into clouds.

The warm front first reveals its presence to watchers at its leading edge, at the very top of the inverted bowl, with high, feathery wisps of cirrus clouds, perhaps 40,000 feet high. The clouds mark the boundary between the warm and cold masses. From overhead, the front slants downwards to the rim of the bowl of cold air beyond the horizon, perhaps some 400 to 500 miles away.

As the cold air retreats, the warm front moves steadily forward at a rate of 10 to 15 miles an hour. As it does so, it brings progressively lower clouds. The lofty cirrus gives way first to high cirro-stratus, then to alto-stratus or alto-cumulus—stratus or cumulus clouds at middle altitudes. Rain may fall at this point, and the atmosphere becomes noticeably warmer and more humid. Finally warm air approaches at ground level, accompanied by low-hanging nimbo-stratus clouds—heavy, turbid layers bringing steady rain. The next day the sun breaks through the layers and a warm spell begins.

When a cold front advances, quite a different sequence of clouds and weather crosses overhead. The mass of cold, dense air bears down on the mass of warm, humid air, ploughing under it and lifting it up, much as a snow shovel pushes under its burden of snow. There is often no warning of its coming; the cold is suddenly present at ground level. A cold front may cause more violent weather than a warm front, but it has its compensations—the bad weather lasts a shorter time. As the front moves

in, the warm air is thrown turbulently upwards, often forming towering cumulo-nimbus clouds that produce violent thunderstorms or extremely heavy showers. Then the sun shines once more, and for a few days the storm clouds are succeeded by so-called fair-weather cumulus clouds that sail white and puffy overhead against a dazzling sky.

Fair-weather cumulus is usually generated by convection caused by ground-level heating. Tall, turreted cumulus clouds, often tens of thousands of feet high, rise over warm bodies of land or water; smaller, less dramatic ones appear over man-made "hot spots"—ploughed fields, sprawling industrial complexes, the sun-scorched pavements and masonry of metropolitan areas.

Good weather usually generates only pure, fluffy cumulus clouds, but on a hot, muggy day, a huge, lowering cumulo-nimbus cloud may form even without the presence of a cold front, piling up so high that ice crystals form at the top, spread out into a distinctive anvil shape by high-altitude winds. Such a cloud can be enormous: six miles or more in diameter and six miles high, containing upwards of half a million tons of water. The ominous appearance of cumulo-nimbus clouds is only a pale reflection of the violent events going on inside them. Miles high, warm at the bottom and cold at the top, they generate both tremendous updraughts and violent downdraughts, sometimes moving at speeds of 200 feet a second, as warm air shoots up and rain shoots down.

The downpour characteristic of the cumulo-nimbus raises a pertinent question. What causes precipitation? Cloud droplets are so tiny and the resistance of air so great that the droplets easily ride in the sky. If they collide, they tend to bounce off one another unless they are extra large. What process brings a million of them together into one raindrop or snowflake heavy enough to fall to earth? Meteorologists puzzle more over how water ever gets down from the skies than over how it gets up.

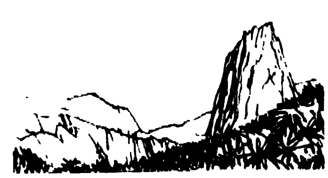
Nobody is certain of the answer, and there is even some disagreement over the theories. Among one group of meteorologists, for example, there is a growing conviction that atmospheric electricity is somehow involved in the creation of precipitation. But most meteorologists believe rainfall occurs in one of two ways, depending on the temperatures of the cloud and the nature of the nuclei it contains.

Rain that falls in splashes

First, warm rain that falls in huge, splashy drops is believed to be caused by a coalescence of the tiny droplets. This is believed to account for tropical rains that cascade from cumulus clouds whose summits are at temperatures considerably above freezing. In hot latitudes, convective currents are particularly strong. Cloud droplets churn upwards at a great rate, and they also drift lightly downwards at the upper limits of the

WIND SWEEPING UPWARDS over high terrain often forms clouds, as airborne water vapour is cooled and condensed by its rapid ascent. The drawings below show three examples of these orographic, or mountain-bred, clouds. At the left, in the Cascades, rising humid air has formed piled-up bands of cirro-cumulus. At the centre, rapid condensation over a South Atlantic island causes turbulence which is visible in hook-shaped wave clouds. Over the Antarctic island at the right, a laminated cloud is formed from an upthrust wind stream made of alternate layers of moist and dry air.

MOUNT RAINIER



GOUGH ISLAND

HEARD ISLAND

updraught. The chances of collision are great. Salt crystals, common in tropic air, offer large nuclei, so that some of the cloud's droplets tend to be slightly larger—and therefore faster-falling—than the average. The falling droplets collide with smaller ones in their downward path and coalesce. The enlarged drops begin to fall at an ever-faster rate, sweeping up more droplets on their way. Eventually they grow large enough and heavy enough to fall out of the cloud as raindrops.

From ice crystal to raindrop

The second way raindrops form accounts for most rainfall in the temperate zones. It was first suggested in the mid-1930's by a Swedish meteorologist, Tor Bergeron. Bergeron wished to explain the fall of rain from clouds in which billions upon billions of tiny droplets float gently, without the larger droplets that characterize the formation of heavy tropical rains. He reasoned that something in the midst of this swarm must pull the droplets together in order for rain to begin. He considered every process he could think of—including electrical attraction—and eliminated all but one as being too inefficient or too slow. He knew that ice crystals, for complex thermodynamic reasons, cause surrounding water droplets to evaporate; the vapour then freezes on the crystals. Ice crystals in the midst of a cloud would qualify as the catalyst necessary to produce rain. In 1935, Bergeron published a paper proposing the astonishing theory that most rain begins as snow.

His theory was later elaborated by a German physicist, Walter Findeisen, and is now widely accepted as the Bergeron-Findeisen theory of rain. It rests on the fact that most rain clouds have some ice crystals in their upper altitudes even in temperate weather. Only a few crystals need be present to start the process. Curiously, minute amounts of pure water, such as exist in clouds, do not ordinarily freeze at 0° C., even when they are condensed on foreign nuclei. They remain a "supercooled" liquid. It has been found in laboratories that such droplets can remain liquid until they cool to −40° C., at which point they all freeze in a rush. However, among all the nuclei in a cloud, a few are impurities that promote freezing at higher temperatures. In almost any cloud whose temperatures at the top are below 0° C., a few ice crystals will form. Around every crystal, droplets evaporate and the ice crystal is enlarged. Crystals may be outnumbered by droplets a million to one, but they cut such a swathe through the surrounding moisture that in the end they triumph. It has been estimated that a snowflake large enough to fall at an appreciable rate can form from a million supercooled cloud droplets in about 10 minutes.

Meteorologists are now persuaded that almost all precipitation except tropical rain begins as these rapidly fattening ice crystals. As the

FOR PROTECTION FROM RAIN, the umbrella became fashionable in the 18th century, although it had been used in Europe as a sunshade since the 16th century. The French dandy pictured in this early-19th century engraving is sporting a folding bumbershoot, equipped with a collapsible case which he carries in his pocket.

crystals grow, they fall and collect more drops, and occasionally another fattened ice crystal. If the weather is cold all the way to the ground, they may arrive as aggregations of crystals, in the incredibly dainty form of snowflakes. Or they may leave the cloud as flakes, hit a layer of warm air several thousand feet above the earth, melt, then strike cold air again near the ground, re-freeze and land as the ice pellets we call sleet. But most often the crystals melt, stay melted, and come to earth as rain.

Hail, the final form of precipitation, is the peculiar product of thunderclouds. According to the most widely held theory, hailstones form when ice crystals are caught in the great updraughts and downdraughts that sweep from the raining bottoms to the freezing tops of thunderclouds 6 to 10 miles high. Alternately melting at the bottom of each ride and re-freezing at the top, the hailstones collect more water on each trip until they become heavy enough to fall to earth. If a hailstone is carefully sliced in half, it will be apparent that it is formed, like an onion, of concentric layers. Each layer is the record of an eventful journey to the freezing summit of the cloud.

A ghastly demonstration of this process was provided in 1930 by five German glider pilots who soared into a thunder-head in the Rhön Mountains. Swept into the cloud's vertical air-shuttle, and afraid their fragile aircraft would be torn apart, all five baled out and opened their parachutes. The updraughts immediately bore them to regions of freezing temperatures and pelting hail. They became human hailstones, falling, rising and freezing. When they finally fell to earth, four of them were frozen stiff. Only the fifth survived.

Among real hailstones, accounts of giants are legion. The official U.S. record is held by one that fell in Potter, Nebraska, in 1928. It measured 17 inches in circumference and weighed one and a half pounds. During the storm that produced this monster, hailstones fell with such impact that many of them were buried in the ground. In other storms, hailstones have killed humans and caused untold damage.

The first cloud-seeding

The ice-crystal theory of rain has led to man's most hopeful attempts to influence the behaviour of clouds since primitive man danced his first rain dance. The artificial seeding of rain clouds was developed in 1946 by General Electric's Vincent J. Schaefer and Irving Langmuir. The principle behind it seems a model of logic and simplicity: to introduce into a cloud of supercooled droplets an agent that promotes the formation of ice crystals. Two agents are commonly used. One is silver iodide, whose crystalline structure is similar to that of natural ice and therefore provides hospitable nuclei on which ice crystals readily form. The

TRYING TO MAKE RAIN with explosives carried aloft by a balloon, the man in this engraving sets off a blast with an electric apparatus and is rewarded by a shower. The picture appeared in an 1880 *Scientific American* article entitled "Novel Method of Precipitating Rain Falls". Invented by Daniel Ruggles, the device was granted a patent.

other agent is solid carbon dioxide, or dry ice, which is so cold that it causes water vapour to solidify into enormous numbers of tiny ice crystals. In either case, precipitation should follow, according to the Bergeron-Findeisen theory. Pellets of dry ice are usually sown into a cloud from aeroplanes. Silver iodide is released as smoke, sometimes from an aeroplane, sometimes from the ground.

Artificial seeding was launched in a wave of optimism. Many farmers and ranchers tried it during the '40's, often with more enthusiasm than good sense. One meteorologist tells of a young pilot who flew aloft and dropped a lump of dry ice overboard—right through the greenhouse roof of the farmer who had engaged him.

By now, however, years of experience have led to a more hard-headed evaluation of the effectiveness of rain-making. The truth is that when rainfall in seeded areas is carefully compared with rainfall in "control" areas, it is almost impossible to tell whether the cloud produced rain because it was seeded or because it was about to rain anyway. The most that can be said is that certain clouds already loaded with moisture do seem amenable to seeding. But scientists are a long way from producing abundant rain where and when it is needed. For some time to come, precipitation seems likely to fall when and where nature wills it, and man will just have to make the best of it, as he always has.

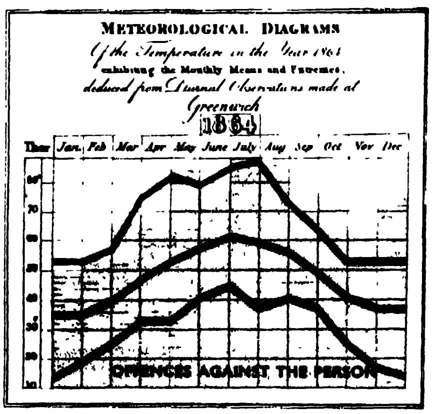
The Mechanics of Rainfall

Rain is the great atmospheric equalizer. Its cycle of evaporation-condensation-precipitation provides a global transfer of two vital quantities—moisture and heat—from places of oversupply to places where they are needed. Water is lifted from the seas and distributed to fields and rivers. Heat is taken into the atmosphere by evaporation, mainly from the tropics; the tropics are thus made livable and their heat, redistributed, makes the rest of the world livable as well. This process produces staggering statistics. One-third of all solar energy reaching the earth is expended in evaporating water; the amount of water involved is about 95,000 cubic miles a year—87,500 million million gallons. Between the time a drop of water evaporates and the time it is precipitated back to earth, it may travel thousands of miles. And no less than a thousand million tons of water rains down on the earth every minute of the day, in a deluge of Biblical proportions.

THE HIGH COST OF WET GROUNDS
In the pouring rain, ground staff pull a huge tarpaulin over the baseball diamond at Chicago's Comiskey Park. Rain is a costly weather phenomenon for baseball; in a recent season it caused postponements 71 times. In the 1962 World Series four games were rained out—at a cost of £175,000, borne by the two clubs, television, the airlines and various other affected enterprises.

influence man in far more complex, obscure and fascinating ways.

Since the late 19th century—when the formal study of the effects of environment on personality first became organized—science has probed the connection between weather and a variety of human activities, from the frequency of cases of assault and battery to the class-room deportment of children, from the circulation of non-fiction in public libraries to suicides, and from the commission of mayhem and murder to the making of love. Data on all these subjects are contained in a voluminously detailed book, *Mainsprings of Civilization*, written by the late Dr. Ellsworth Huntington of Yale. In humid weather in Denver, Colorado, schoolchildren had to be disciplined five times as often as they did in dry weather. In public libraries in eight cities in North America, people withdrew books of serious non-fiction much more frequently in late winter and early spring than at other times of the year.



TEMPERATURE AND CRIME are correlated in this graph drawn from statistics compiled in London for the year 1864. The three lines represent the low, average and high temperatures for each month. The bars stand for the number of people arrested for criminal offences. The fewest arrests (624) were made in January, the most (1,243) in July.

In his book *Climate Makes the Man*, Dr. Clarence A. Mills, Professor of Experimental Medicine at the University of Cincinnati, claims that bad moods and falling barometers go hand in hand. On a day when the humidity is low and the barometer is rising, the average man tends to go about his daily work cheerfully, function more efficiently and look upon life with optimism. But the same man on a muggy day in August growls at his children, snaps at his fellow workers, is gloomy, sullen and pessimistic. Under normal circumstances most people muddle through such weather-induced distress; perspective and a sense of humour come to their rescue. But for people whose physical condition is already below par the oppressive effects of bad weather can tip the balance from marginal health to serious illness. And for people already under emotional stress, it may trigger explosive acts of aggression.

Hot tempers in the Punjab

Of the 148 religious riots that occurred in India between 1919 and 1941, says Dr. Huntington, more than one-third took place in the most uncomfortable months, April and August. The figure drops slightly in May and June, when the monsoon season brings cool winds and showers to relieve the blistering heat and parched air. But it begins to rise again in July, when the wind slackens off and the air becomes soggy.

In another classic study—by a pioneer in the field of weather influence, O. E. Dexter—weather emerged as a probable factor in assault-and-battery arrests. Studying some 40,000 such arrests in New York City, Dexter found that the rate of increase exactly paralleled the rise in temperature. In January the figure for arrests was low, in July it hit its peak—only to fall off during the devitalizing mugginess of August. "Temperature, more than any other condition," Dexter concluded, "affects the emotional states which are conducive to fighting." He may

have overstated the case a bit, but his figures apparently established a clear relationship between tempers and temperature.

Winds that blow steadily and monotonously for weeks on end have long been credited with a profound influence on people. The depressing and deranging effects of the Alpine *Föhn*, mentioned in Chapter 3, are only one example. In southern France, the *vent du Midi*, a warm and moist wind, is commonly held responsible for headaches, rheumatic pains, epileptic fits, asthma attacks and certain kinds of infant fever. The people of Tangier blame headaches and feelings of oppression on the levanter, an east wind from the Mediterranean. North Africans believe that the sirocco, a hot, dusty wind that blows off the Sahara, depresses people to the point of suicide. And a nameless east wind that blows over London in November and March was actually linked by an 18th-century British court physician to regicide. This wind, the French writer Voltaire quotes the doctor as saying, caused "black melancholy to spread over the nation". Dozens of dispirited Londoners hanged themselves, animals became unruly, people grew grim and desperate. "It was literally in an east wind", the doctor told Voltaire, "that Charles I was beheaded and James II deposed."

Débris in the wake of a wind

The healthiest weather for the majority of people is not necessarily good weather. Some doctors believe that any weather condition, good or bad, may have unfortunate results if it persists too long. For one thing it is depressing simply because it is so monotonous. But it is also harmful physically; the body becomes less adaptable to change and is therefore more vulnerable to changes when they do occur. Yet frequently changing weather can also be unsettling. The foremost agency of sudden reversals in the weather, the cyclonic storm, also seems to trigger off profound disturbances in men's minds and bodies. The cyclonic storms that regularly sweep down over the U.S. Mid-West are described by Dr. Mills as "leaving behind them a trail of human wreckage—cases of acute appendicitis, respiratory attacks of all kinds, and suicides".

Even people not suffering from such afflictions are unsettled by these storms, Dr. Mills reports. As the storm front approaches and the barometer falls and humidity rises—people are unaccountably bothered by "a feeling of futility, an inability to reach the usual mental efficiency or to accomplish difficult tasks". Children become irritable and petulant, adults quarrelsome and fault-finding. "Such weather", Dr. Mills cautions, "provides the most perfect background for marital outbursts."

As the storm front passes, the weather and the emotions do an about face. The humidity falls, the barometric pressure rises, the air becomes cool, clear and invigorating; people's spirits become buoyant and diffi-

cult tasks are accomplished with ease. It would be a fine thing, Dr. Mills concludes, if musicians and other performing artists could schedule their public appearances for such weather: audiences would invariably hear them at their best.

Apparently a great many organisms respond in some fashion to changes in humidity and atmospheric pressure. Farmers claim that the behaviour of their animals warns them as much as a day in advance when a storm is approaching: normally docile horses and cows turn perverse and unruly. Dogs are said to be able to "smell" a storm coming; they grow restless and edgy, and may run away. Fishermen claim that fish bite better just before a storm. And ants, responding to some mysterious detection system of their own, scurry about as the pressure drops, shoring up their tunnels against the approaching deluge.

Some people also appear to have a sixth sense about a coming storm: it seems to function with special sharpness in the aged, the allergic, the overweight, the chronically ill and the hypersensitive. They feel it in their bones, their joints, their muscles, their sinuses, the palpitations of their hearts. They even feel it in the scars of old football injuries. Imagination? Not necessarily. Scientists have detected measurable changes within the body that correspond to changes in atmospheric pressure — especially in the old, infirm and emotionally unstable whose biological processes may be unusually sensitive. Changes in pulse and respiration rates, blood pressure, blood composition and various physical processes systematically reflect the transit of the low-pressure and high-pressure air masses that regularly precede and follow a storm.

Arthritic pains on order

In a recent two-year study at the University of Pennsylvania School of Medicine, 30 arthritic patients were sealed in room-sized climate chambers for periods of two to four weeks. Temperature and rate of air movement were changed without producing any effect on the patients. But when researchers simulated approaching storm conditions—gradually dropping pressures from 31.5 to 28.5 inches and boosting humidity from 25 to 80 per cent– the results were astonishing. Eight out of ten patients reported stiffness and swelling in their joints, and some reported the symptoms within minutes of the change.

There are equally dramatic examples of the elation that appears to follow the breaking of a storm. Dr. Huntington reports the experience of a group of freshmen at Massachusetts State College at Amherst, who were taking an intelligence test at the time of the New England hurricane of 1938. Outside the wind howled at 80 miles an hour, the sky turned dark, trees crashed to the ground, electric power lines snapped. It was, college officials thought, the worst kind of weather for an examination,

and they expected it would show up in the marks. And yet, when the results came in, they showed a jump in percentage averages from 75 to a staggering 95. Apparently the storm had acted as a powerful mental stimulant, and perhaps the stimulation came from atmospheric turbulence.

Is it true that changes in atmospheric pressure affect our thoughts and feelings? If so, how does it happen? Science does not know the answer to either of these questions, but some scientists think they may have a clue. They think that the key may lie in ions—tiny, electrically charged particles of matter that exist in the atmosphere.

Some ions are positively charged, and some are negatively charged. Usually they exist in the air in a ratio of 5 positive to 4 negative. And to some scientists, this is a critical balance. Negative ions are partly composed of oxygen, which can be beneficial to the human body; positive ions are partly composed of carbon dioxide, which can be harmful.

For a number of years ionization researchers have speculated on the possibility that a greater-than-normal number of positive ions in the air might exert a measurable effect on the body's functions by slowing down its responses. Significantly, among the agents that are known to produce an imbalance of positive ions are smog and certain kinds of heating and air-conditioning equipment.

In an experiment conducted at New York University's College of Engineering, volunteers were exposed to streams of negative ions, and then given a series of tests which showed that their visual responses had perked up measurably and that they could work much harder without showing fatigue. In a similar study at the University of California, Dr. Albert P. Krueger found that an excess of negative ions caused the body's respiratory system to function better.

Two other ion researchers—Dr. C. W. Hansell, a former RCA research scientist, and Dr. Igho Kornbluch, of the Graduate Hospital of the University of Pennsylvania—have suggested that various conditions in the atmosphere itself may produce an imbalance of ions. Perhaps the air just before a storm is overloaded with positive ions, and therefore with carbon dioxide. And perhaps the balance tips the other way when the storm breaks, dumping an overload of negative ions—and oxygen—into the air. The carbon dioxide could account for the depressing biological effects, and the oxygen for the feeling of elation—since oxygen, taken straight, is a heady stimulant.

Machine-made moods

Dr. Hansell first became aware of these effects accidentally. Back in 1932 he noticed that one of his fellow scientists at RCA, who was working with a device called an electrostatic generator, went through strange reversals in mood. Sometimes the scientist finished the working day in

high spirits, while on other days he was short-tempered and gloomy. Neither mood could be attributed to the actual progress of the work itself. The man noticed it too, and became curious. He began to keep track of his changing moods and found that he was cheerful when the generator was set to produce negative ions and depressed when it was set to produce positive ones. Shortly afterwards, reports from systematic ionization-research studies in Europe confirmed these observations.

Hansell and Kornblueh can only speculate at how the ion balance in the earth's atmosphere changes. In the case of cyclonic storms, the changing pressure may somehow result in the presence of more of one or the other. But the depressing effects of steady winds—which, according to their theory, would also be caused by an overdose of positive ions—cannot be explained in this way. Perhaps, they suggest, the winds liberate positive ions by stirring up sand and dust.

If it is true that ions in the atmosphere affect man biologically, it is equally true that it will be a long time before he can put this information to use outside the laboratory. Mankind is not about to alter the air's ion content by manufacturing weather. For a good many years to come, man will have to cope with weather much as he has always coped with it—by accommodating to it when he must, exploiting it when he can and running away from it when it becomes intolerable.

Meteorology in Miniature

It is customary to think of weather as something vast and global, as a series of great highs and lows and frontal systems marching across a weather map, dispensing rain or sunshine over large areas of the earth. But there is another kind of weather, which exists on a small and often personal scale: the cool shadow a barn casts during a steamy summer day, the welcome wind-break a row of trees provides in a stiff winter wind, or a hothouse in which plants may grow amid freezing wastelands (*opposite*). This is microweather, the weather that affects us most directly, and the only kind man has been able to influence. Microweather is always local, even minute, but it is significant none the less. It is a citrus farmer saving his crop by lighting smudge pots on a cold night. It is a boy and his boat finding shelter from a squall in a tiny cove. Likewise, it is a cinema marquee that protects a new hairdo from a shower on the afternoon before an appointment.

AN ANTARCTIC HOTHOUSE
At Wilkes Station inside the Antarctic Circle, where the average outside temperature in summer is only about $-1°$ C., a Plexiglas bubble serves as a makeshift miniature greenhouse in which radish, lettuce and tomato plants flourish and even yield some fruit. This example of man-made microweather was created more for the sake of decoration and cheer than for survival.

THOUSANDS OF YEARS AGO, understanding the weather was a simple matter of understanding what days were good for hunting and what days were not. Today it is one of the most complicated problems of modern science, involving the reduction of masses of weather data to simple terms that can be dealt with mathematically—a formidable task.

In 1946 the late John von Neumann, one of the most brilliant and versatile mathematicians of modern times, gave the task to a computer. Computers were then comparatively untried, but von Neumann's, the MANIAC, had just completed the stupendous calculations that resulted in the hydrogen bomb. He was casting about for another task worthy of the machine's amazing speed and capacity, and he found such a challenge in meteorology. In fact, he found not one, but dozens. "The hydrodynamics of meteorology", von Neumann told a group of fellow scientists some 10 years later, "presents without doubt the most complicated series of interrelated problems not only that we know of, but that we can imagine."

Consider, for a moment, the characteristics of a given parcel of air. It has measurable pressure, temperature, density. It contains water vapour, some of which may be condensed or frozen around tiny particles of matter called nuclei. It swarms with the electrically charged atoms called ions. All these characteristics vary from instant to instant. Moreover, they interact. A change in one produces a chain reaction of changes in the others. In addition, the parcel moves as a mass—up, down, horizontally, obliquely, in circular swirls. And as it moves, it collides, intermingles and interacts with other similarly complicated air parcels.

Blend into this the force exerted by the earth's rotation, the turmoil of clashing warm and cold air masses, the churning turbulence caused by the obstruction of mountains, the drives of the global wind systems, and the thermal influence of sun and oceans. The result is a self-perpetuating chaos whose reduction to any sort of simple, logical pattern has regularly defeated even the most rational and systematic scientific research. Only in recent years, with the wizardry of electronics—taking the form of such tools as radio, radar and, above all, the computer—has real help arrived. Now, for the first time, young meteorologists on the threshold of their careers can look forward to solving within their lifetimes some of the problems that were the fascination and despair of their predecessors.

Today's meteorologists consider themselves to be physical scientists, and meteorology to be the physics and chemistry of the atmosphere. The atmosphere, they say, is an enormous and elaborate system of interacting parts, each behaving according to fixed, unchanging laws—the same laws that govern the behaviour of all matter. Weather is the result of these laws, and is therefore scientifically predictable.

And yet, for many centuries the prediction of weather was based not

A PERILOUS EXPERIMENT
Lightning leaps from an iron rod, killing a Russian scientist, Georg Wilhelm Richmann, and bowling over his assistant as they investigate the nature of lightning in 1753. The writings of Benjamin Franklin inspired this experiment, but it was a simpler technique—a kite with a key at the end of the string—that led Franklin to his discovery that lightning is electricity.

on law but on previous performance. Men saw that weather followed certain more or less predictable patterns, but they were more interested in charting the patterns than establishing the basic causes. In fact they became quite ingenious at measuring and plotting the possible course of the weather, as a later look at their tools and methods will show.

It was another group of men—some of them not even interested in weather at all—who developed the principles that became the basis for the science of meteorology. Some of these early investigators were themselves scientists—chiefly astronomers and mathematicians—but their ranks also included sea captains, glass-blowers, schoolteachers, priests and even a kite-flying diplomat.

The structure of weather

In seeking to probe the mysterious forces of the atmosphere, these men fashioned instruments that sensed and measured changes in temperature, pressure, humidity and the speed of the wind. They named clouds, watched storms, rode out typhoons and hurricanes, and painstakingly logged what they felt and saw. Slowly, out of their accumulated experiences and speculations, the true nature of weather emerged. It had, they saw, organization and structure. One day's weather was the result of things that had taken place in the atmosphere on the preceding day, and the forces that produced weather were inevitable and unchangeable—in other words, natural laws.

ATMOSPHERIC PRESSURE, or the weight of the air, was demonstrated experimentally in 1644 by Evangelista Torricelli. A glass tube (B) filled with mercury was inverted and its mouth inserted in a bowl of mercury. The level of mercury in the tube dropped only slightly, indicating that some force was pressing down on the mercury in the bowl: the weight of the surrounding air. The experiment was verified in a different form with another tube (A).

One of the earliest of the weather theorists was the Greek philosopher Aristotle, who lived from 384 to 322 B.C. "The whole terrestrial region", wrote Aristotle in his *Meteorologica*, was composed of four "bodies": fire, air, water and earth. He believed that these bodies "are transformable one into another, and that each is potentially latent in the others". For the most part, he said, the transforming agent was the sun. From the waters of the earth it drew a cool, moist substance, and from the earth itself it drew something hot and dry, "a kind of smoke"—the stuff that "we are accustomed to call fire". This dry exhalation formed "the origin and natural substance of the winds", and was also responsible for earthquakes and comets. In combination with the cool, moist substance, it formed air. And air, as it underwent temperature changes, turned into clouds, rain, snow, frost or dew.

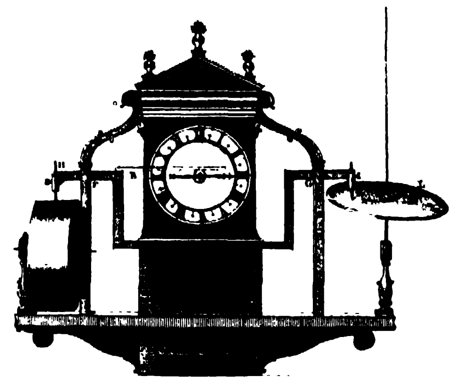
Aristotle even had an explanation for thunder. When a cloud cools and condenses, it forcibly ejects the wind it contains; the noise is the sound the wind makes when it hits the surrounding clouds. As for lightning, Aristotle wrote, "As a rule the ejected wind burns with a fine and gentle fire, and it is then what we call lightning".

For 2,000 years Aristotle's fanciful reasoning was taken for fact. But in 1543 the Polish astronomer Copernicus suggested that the earth was

only a minor member of a vast solar system—and *Meteorologica*, with its earth-centred universe, gradually lost its authority. Men no longer consulted mystics and seers for information on the weather. Instead, they began to study observable facts.

Soon after Galileo had made his thermometer, around 1600, his pupil Evangelista Torricelli constructed a barometer out of a glass tube and a basin of mercury. By the end of the 15th century there were crude but effective instruments for measuring humidity. One of the earliest, called a hygroscope, was described by the German cardinal Nicolaus de Cusa: "If you suspend from one side of a large balance a large quantity of wool, and from the other side stones, so that they weigh equally in dry air, then you will see that when the air inclines towards dampness, the weight of the wool increases, and when it tends to dryness, it decreases."

In England, during the 17th century, the philosopher-inventor Robert Hooke make a hygroscope that exploited the water-retaining properties of the bristle of the wild oat; he also developed an improved version of a gauge for determining the strength of the wind. Along with two other countrymen, Sir Christopher Wren and Richard Townley, he also designed a gauge for measuring rainfall. But Hooke's most ambitious meteorological device was an elaborate assemblage of instruments which he called a weather-clock. The weather-clock measured not only time but also temperature, pressure, humidity, rainfall, and the strength and direction of the wind. Unfortunately this mechanical marvel was often in need of repairs.



A WEATHER-CLOCK, one of the first self registering instruments for measuring weather change was invented in 1663 by Sir Christopher Wren, the English architect and scientist Driven by an ordinary clock, it enabled a drum-like barometer (*left*) and a wind vane to make a pencilled 12-hour record of their readings But it took another 200 years for the science of meteorology to become sophisticated enough to utilize such devices.

Laws of the solar system

At the same time men like Galileo, the Danish astronomer Tycho Brahe, the English curate Jeremiah Horrocks and the German astronomer Johannes Kepler were conducting studies that had no immediate connection with weather, but were ultimately to play a part in the beginnings of meteorology. They were studying the behaviour of the solar system—and by inference, the nature of laws that controlled it. Galileo, Brahe and Horrocks plotted distances between the earth and the sun and between the earth and the moon with greater and greater accuracy, and in 1609 Kepler showed that the earth's orbit was elliptical. Their work—particularly Kepler's—was an important influence on Sir Isaac Newton, whose *Philosophiae Naturalis Principia Mathematica*, published in 1687, is generally acclaimed to be the most stupendous achievement in the history of science.

The *Principia* argued that all matter, from the smallest particle to the largest planet, responded to certain laws of gravitation and motion. All of the *Principia*'s laws are important, but the Second Law of Motion is one of the corner-stones of modern meteorology. The Second Law says

that a body whose motion is changed by an outside force will accelerate in the same direction as the force, and at a rate directly proportional to the amount of the force.

But although the Second Law is important for what it says, it is almost more important for how it says it. Expressed as the mathematical equation $F = ma$ (force equals mass times acceleration) it is extremely useful to meteorologists, since force, mass and acceleration are all significant factors in the atmosphere.

But marvellous as it was, Newton's *Principia* was not enough. There were still many intricate workings of the weather that it did not explain. Key principles, key equations were missing. One of the earliest of these additional principles was discovered in the middle of the 17th century by a contemporary of Newton's, the Irish physicist Robert Boyle. It concerns the relation between the volume of a body of air and its pressure.

According to Boyle's Law, "At constant temperature, the volume of a gas varies inversely with its pressure". In other words, if a body of air is made to decrease in size, its pressure increases, and *vice versa*. Inflate a toy balloon, then squeeze its air into a smaller and smaller volume; as the air is reduced in volume, its pressure rises until, squeezed enough, it will burst out of the balloon.

Then, in the late 18th century, as an outcome of his studies into the nature of gases, the French physicist Jacques Charles discovered a connection between the volume of a gas and its temperature. Charles's Law says that when the pressure of a gas remains constant but its volume changes, there is an accompanying proportional change in temperature. In other words, the hotter a gas, the greater its volume. Out of the Law came mathematical equations for calculating the contraction of cooling air and the expansion of air that is being warmed. Charles's Law is sometimes attributed to another Frenchman, Joseph Gay-Lussac, who was performing similar experiments at the same time. The principle, in either case, was an extension of Boyle's Law, adding to Boyle's the important factor of temperature. Before long, it was commonly linked with Boyle's in the now classic Boyle-Charles, or General Gas, Law.

Dalton and the barometer

Shortly after the discovery of Charles's Law came the discovery of still another principle vital to meteorology. Between 1788 and 1792 an English chemist, John Dalton, conducted a number of experiments concerned with barometric pressure. Dalton was looking for connections between the behaviour of the barometer and certain atmospheric conditions—rain, the direction of winds, the heating and cooling of air. Out of his investigations he formulated a law, sometimes called Dalton's Law, sometimes the Law of Partial Pressures. It says that in a mixture of

gases, each gas will exert the same pressure as it would if it were alone, unmixed. It also says that the total pressure of the mixture of gases is the sum of their individual pressures. Armed with Dalton's Law, meteorologists can calculate the amount of water vapour in the air—and thus describe the formation of clouds, fog, rain and snow in mathematical terms.

From Newton to Dalton, men had discovered the laws governing most of the factors in the atmosphere that influence weather. One more principle was needed, one that stated the relationship between heat and the changes it causes in the air's temperature, pressure and volume.

Nature's indestructible energy

One of the key principles derived from Newton's system was the Law of the Conservation of Mass. It stated that mass, or matter, could be neither created nor destroyed; it could only be changed from one form to another. A blazing log does not disappear; it becomes ashes and gases. Boiling water turns into steam. In the 1840's physicists began to suspect that the same thing might be true of energy. Perhaps it, too, was never created or consumed, but simply passed from one form to another. One of these forms was called potential energy, or stored energy. When a clock is wound, the energy spent in turning the key is transmitted to, and stored in, the tightly coiled mainspring. The other form of energy is kinetic energy—the energy of motion. A boulder pushed off a cliff and sent crashing into the canyon below has kinetic energy, devastating and murderous, crushing whatever blocks its path.

One of the 19th-century scientists who was convinced that energy was indestructible was the English physicist James Joule. In his most celebrated demonstration Joule used the kinetic energy of a falling weight to turn a miniature paddle wheel. The paddles churned the water and created friction, thus raising the water's temperature. Joule measured the energy delivered to the paddles by the falling weight and then measured the rise in temperature. They were proportional. The kinetic energy had not been lost or dissipated, it had simply been transformed into another form of energy—thermal energy.

Not long after Joule performed his experiments a young German scientist, Hermann von Helmholtz, stated the principle as a law. It is sometimes called, logically enough, the Law of the Conservation of Energy, but it is far better known in the world of modern science as the First Law of Thermodynamics. It says, in effect, that when a gas is heated, the amount of heat added equals the change in the internal energy of the gas, plus the work that the gas does in expanding. Without deliberately seeking it, Helmholtz had chanced upon the last piece of the weather puzzle.

Almost as fast as the theories of Newton, Boyle, Charles, Dalton and

ROBERT BOYLE (1627-1691)

FORMULATORS OF THE LAW of gases, Robert Boyle and Jacques Charles gave meteorology one of its first physical principles. Working 100 years apart, the two men explained the relationships of temperature, volume and pressure in all gases, including air.

JACQUES CHARLES (1746-1823)

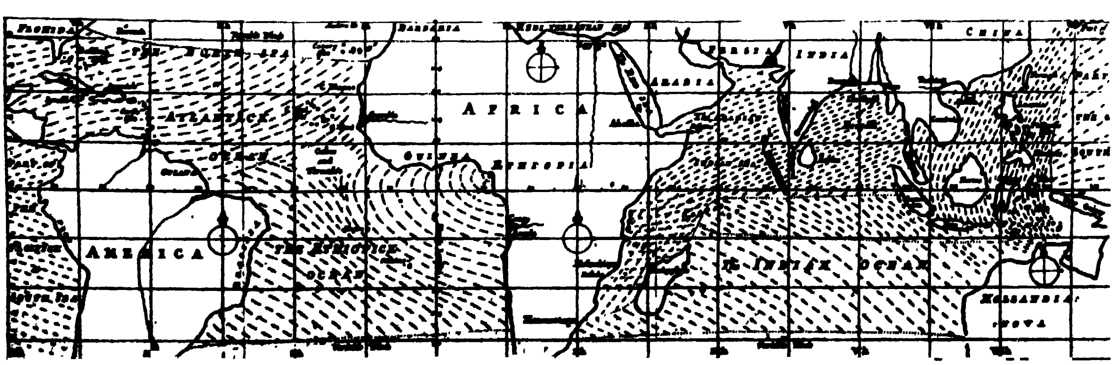
Helmholtz appeared, other men began to apply them to the study of the weather. One of the most gifted of these men was Edmund Halley, Britain's Astronomer-Royal from 1720 to 1742. Friend of Newton and financial backer for the publication of his *Principia*, Halley was a dedicated scientist and cataloguer of stars. He discovered the comet that bears his name, and became a student of Arabic languages in order to read the records of ancient astronomers. Halley made numerous contributions to the science of weather, but his greatest one is a celebrated memoir on the cause of tropical trade winds and monsoons, illustrated with history's first meteorological map. Not all of the memoir's contents are original, and some of its assumptions are naïve, but it marks a meteorological milestone—a first attempt to combine theories about the atmospheric processes with first-hand observation of their results.

Halley based his conclusions partly on his own observations, made at sea and during a two-year stay on the island of St. Helena, and partly on information he collected from globe-trotting mariners. It seemed to him that trade winds and monsoons were caused by the actions of the sun upon the air over the equator. The heated air rose, pulling cooler air in from the south and north. Or, to quote Halley's own words, the movement of the winds was due to "the Action of the Sun's Beams upon the Air and Water, as he passes every day over the Oceans, considered together with the Nature of the Soyl, and the Situation of the adjoyning Continents: I say therefore, first, that according to the Laws of Staticks, the Air, which is less rarified or expanded by heat, and consequently more ponderous, must have a Motion towards those parts thereof, which are more rarified and less ponderous. . . ." Halley's views on this score coincide fairly closely with modern theory. But when he attempted to explain why the trade winds blow from the north-east in the Northern Hemisphere and from the south-east in the Southern Hemisphere, Halley's hypothesis faltered. He could only suggest that they follow "the Sun continually shifting to the Westwards".

The secret of the trade winds

In 1735, some 50 years after the publication of Halley's paper, George Hadley, a London lawyer and philosopher, presented a clearer and much more accurate explanation of the direction of the trade winds. Hadley agreed with Halley that solar radiation and thermal convection accounted for the existence of the trade winds. But the westward movement of the winds was really caused, Hadley said, by the west-to-east rotation of the earth. "The air," said Hadley, "as it moves from the Tropicks towards the Equator, having a less Velocity than the Parts of the earth it arrives at, will have a relative Motion contrary to that of the diurnal Motion of the Earth. . . ."

THE FIRST MAP OF THE WINDS was the work of Edmund Halley, who is best known as an astronomer but who also made the first modern study of the general circulation of the atmosphere. His article, which appeared in 1686 together with the map shown below, described the trade winds and doldrums in the tropics. He correctly attributed them to thermal convection—the rising of tropical air and its distribution outwards from the equator.



Hadley took account of the fact that the earth's surface is moving faster at the equator than it is north or south of it. In other words, it spins through more miles in one minute at the equator than it does, say, 45° north of the equator. Therefore, reasoned Hadley, a current of air moving towards the equator would lag behind the spinning earth, hitting the equator at a point slightly behind the north-south axis from which it started. Thus it would seem to be moving in a westerly direction. Hadley's reasoning is very close to the currently accepted explanation which assigns the cause to the Coriolis force.

A pirate in a sea of fire

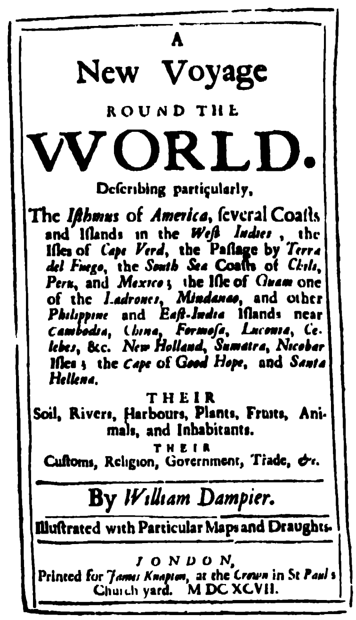
Meanwhile, the day-to-day weather and storms in particular—was also being closely observed and catalogued by men whose association with it was much more personal. The first description of a typhoon, now a classic of the sea, came from the log of a buccaneer, Captain William Dampier, a contemporary of Halley's. The typhoon caught the pirate captain off the China coast on the afternoon of the 4th July 1687, striking from the north-east. Wind howled through the rigging, rain fell in torrential sheets, and towards midnight "it thundered and lightned prodigiously, and the Sea seemed all of a Fire about us: for every Sea that broke sparkled like Lightning".

The eye of the storm passed the next morning "and the Sea tossed us about like an Egg-shell, for want of wind". Shortly after noon on the second day the wind came at Dampier from the opposite point of the compass, the south-west, and the second stage of the typhoon struck the battered vessel. "We presently brail'd up our Mizen, and wore our Ship; but we had no sooner put our Ship before the wind, but it blew a Storm again, and it rain'd very hard; though not so violently as the night before; but the wind was altogether as boysterous, and so continued till 10 or 11 a clock at night. All which time we scudded, or run before the Wind very swift, tho' only with our bare Poles.

"I was never", concludes the captain, "in such a violent Storm in all my life; so said all the Company."

In Philadelphia in 1743, Benjamin Franklin, quite by accident, hit upon the prevailing south-west-to-north-east drift of Atlantic coastal storms. For weeks Franklin had been eagerly looking forward to an eclipse of the moon that was due to occur at 9 p.m. on the 21st October, but to his intense dismay clouds gathered on that very afternoon. "Before 8," he later noted, "a storm blew up at NE and continued violent all Night and all next Day . . . so that neither Moon nor Stars could be seen."

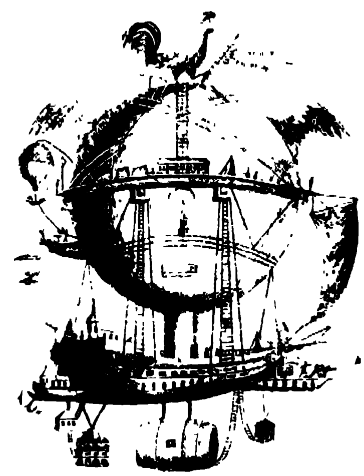
Several years later, recalling the storm in a letter to a friend, Franklin observed that "what surpriz'd me, was to find in the Boston Newspapers an Account of an Observation of that Eclipse made there: For I had


A
New Voyage
ROUND THE
WORLD.
Describing particularly,
The *Isthmus* of *America*, several Coasts and Islands in the *West Indies*, the Isles of *Cape Verd*, the Passage by *Terra del Fuego*, the *South Sea* Coasts of *Chili*, *Peru*, and *Mexico*; the Isle of *Guam* one of the *Ladrones*, *Mindanao*, and other *Philippine* and *East-India* Islands near *Cambodia*, *China*, *Formosa*, *Luconia*, *Celebes*, &c. *New Holland*, *Sumatra*, *Nicobar* Isles; the *Cape* of *Good Hope*, and *Santa Hellena*.
THEIR
Soil, Rivers, Harbours, Plants, Fruits, Animals, and Inhabitants.
THEIR
Customs, Religion, Government, Trade, &c.
By *William Dampier*.
Illustrated with Particular Maps and Draughts.
LONDON,
Printed for *James Knapton*, at the *Crown* in St *Paul's* Church yard. MDCXCVII.

A SCIENTIFIC BUCCANEER, the 17th-century sea captain William Dampier is credited by modern meteorologists with being a pioneer collector of weather data. In 1697, following an eight-year voyage that combined scientific research with piracy, Dampier published the book whose title appears above. In it he described—in detail and for the first time—a China Sea typhoon

thought, as the Storm came from the NE, it must have begun sooner at Boston than with us, and consequently have prevented such Observation." At the same time he noted that a severe storm had hit Boston on the following day, the 22nd, sweeping high tides across the wharves, smashing small craft and flooding streets along the Boston water-front.

It must have been, Franklin reasoned, the same storm. And in spite of its north-east surface winds, it must have been travelling from the south-west. "Upon comparing all the other accounts I received from the several colonies, of the time of the beginning of the same storm, and, since that of other storms of the same kind," he wrote later, "I found the beginning to be always later the farther northeastward. I . . . cannot, from memory, say the proportion of time to distance, but I think it is about an hour to every hundred miles."



A SUPER-BALLOON for meteorologists, the *Minerva*, dreamed up in 1804 by a French balloonist named Etienne Robertson, was designed to carry 60 meteorologists and astronomers—the pick of the learned societies—on a round-the-world voyage of observation. The balloon was to carry a fully equipped observatory, a study for the scholars, and a banner with a Latin motto meaning "for the sake of knowledge." Not surprisingly, the *Minerva* never got off the drawing board

The hurricane's whirling winds

Nearly 80 years later, similar first-hand observation by an inquisitive Connecticut storekeeper led to meteorology's first accurate description of the wind system of a tropical hurricane. A few weeks after the great September hurricane of 1821 had battered the Atlantic Coast and western New England, storekeeper William C. Redfield travelled across storm-ravaged Connecticut, and noticed a strange thing. In the vicinity of his home in the central part of the state, the hurricane had toppled trees towards the north-west. But 40 or 50 miles to the west, in Litchfield County, the storm had blown down trees in the opposite direction. This could only have been done, he correctly surmised, by a whirlwind.

Several years later, on a boat trip across Long Island Sound, Redfield fell into conversation with Professor Denison Olmsted of Yale. Like many such conversations, this one turned upon the weather, and the two men fell to reminiscing about the hurricane. Redfield's observations fascinated Olmsted, and he encouraged the storekeeper to continue his research. For years after that, Redfield collected data about hurricanes and other violent storms. He pored over ships' logs, interviewed sea captains, collected newspaper cuttings.

In 1831, 10 years after his post-hurricane trip across Connecticut, he published an historic meteorological paper, "Remarks on the Prevailing Storms of the Atlantic Coast of the North American States", in the *American Journal of Science and the Arts*. It advanced a remarkable hypothesis, long since confirmed: that a hurricane has a rotary, counter-clockwise wind system with a central eye of calm, and that, although its winds are fierce, its actual progress is slow.

Twelve years later a professional balloonist, John Wise, wrote a harrowing account of his nightmarish experience in the violent convection updraughts of a thunderstorm near Harrisburg, Pennsylvania.

"The first sensations", he wrote, "were extremely unpleasant. . . . The cold had now become intense, and everything around me of a fibrous nature became thickly covered with hoarfrost, my whiskers jutting out with it far beyond my face, and the cords running up from my car looking like glass rods, these being glazed with ice and snow, and hail was indiscriminately pelting all around me. . . . I soon found myself whirling upward with a fearful rapidity, the balloon gyrating and the car describing a large circle in the cloud. A noise resembling the rushing of a thousand milldams, intermingled with a dismal moaning sound of wind, surrounded me. . . . The balloon subsided only to be hurled upward again, when, having attained its maximum, it would again sink down with a swinging and fearful velocity, to be carried up again. . . . This happened eight or ten times, all the time the storm raging with unabated fury. . . .

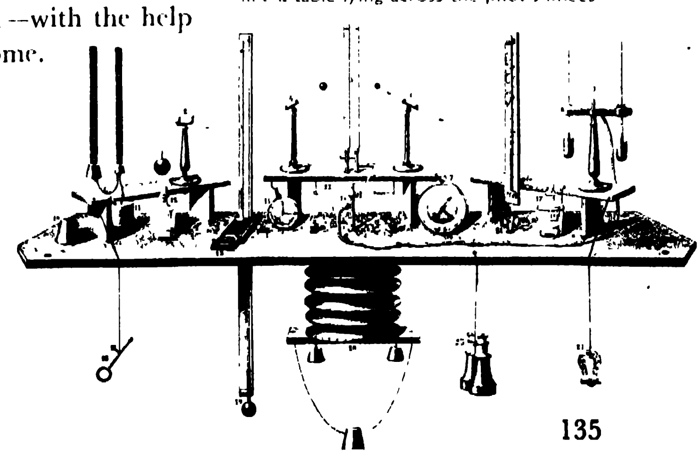
"Once I saw the earth through a chasm in the cloud, but was hurled up once more after that, when, to my great joy, I fell clear out of it, after having been belched up and swallowed down repeatedly by this huge and terrific monster of the air for a space of twenty minutes. . . . I landed, in the midst of a pouring rain, on the farm of Mr. Goodyear, five miles from Carlisle, in a fallow field, where the dashing rain bespattered me with mud from head to foot, as I stood in my car looking up at the fearful element which had just disgorged me."

Looking back on the history of their profession, meteorologists generally consider that its theoretical and practical aspects finally began to merge around 1900 in the work of an extraordinary group of scientists at the Norwegian Geophysical Institute, the Bergen School, led by Vilhelm Bjerknes. By Bjerknes' time, weather data had become more accurate and, thanks to such technological advances as the telegraph, more comprehensive. Bjerknes dared to suggest that day-to-day weather forecasting could be elevated from educated guesswork to an exact science. He first broached the concept in 1904, in a paper entitled "Weather Forecasting as a Problem in Mechanics and Physics".

A meteorological chess-board

The Bjerknes system was simple and straightforward, with the logical inevitability of an end game in chess. It outlined a meteorological operation that would begin with a data-collecting network, as far-ranging as possible. The network would gather regular readings of temperature, pressure, humidity and wind velocity at the earth's surface and in the upper air. From these data a graph, or map, would be made, showing what Bjerknes called "the initial state of the atmosphere"—the weather as it existed at the time of the readings. Then the data would be translated into mathematical terms, and these would be used—with the help of mathematical equations—to compute the weather to come.

AN INSTRUMENT PANEL for meteorological balloon ascents was invented by the English scientist James Glaisher for use on his first flight in 1862. Its instruments included several thermometers (1,4,5), two barometers (3,7), a compass (13) and opera glasses (23). The panel was attached to the balloon's basket like a table lying across the pilot's knees.



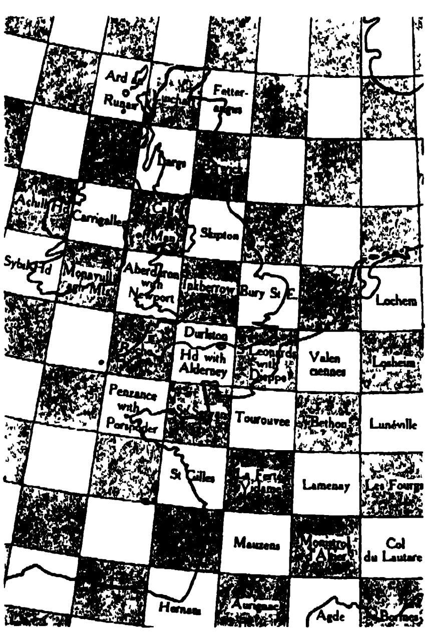
Bjerknes worked very hard to put his system into practice, and although the effort never completely succeeded, it did produce some remarkable side effects. During World War I, when Norway was cut off from foreign weather reports, Bjerknes saw that he would need data from more stations, including some on board ship—and this would cost more money. To get it, he went to the Norwegian fishing-fleet operators and cannily suggested that for the equivalent of a few herring in kroner they could have much more precise weather predictions. The fishermen saw his point and chipped in, and Norway got a world-famous weather service. One consequence of the service was a new meteorological theory. With the intensified coverage that the service provided, the Norwegian scientists were able to confirm a suspected relationship between air masses and the formation of cyclones. The relationship is most closely associated with the name of Bjerknes' son, Jakob, and it is called the "polar-front" theory.

The meetings of the air

According to this theory, a great mass of cold polar air flows generally from east to west in the far northern latitudes. Farther south, in the mid-latitudes, another mass of warmer, moisture-laden air moves from west to east. The front itself—a term analogous to the "front" of a battlefield, where two opposing forces meet—is the surface where the two air masses meet. But the word "front" is slightly misleading. Polar easterlies and mid-latitude westerlies do not confront each other head on; rather, they speed past each other, like trains travelling in opposite directions on adjoining tracks.

Though many other factors may be involved in the formation of a cyclone, it usually starts out as a disturbance in the flow of these two great currents. Any number of things may cause such a disturbance—for example, the interference of a range of mountains, or the difference between sea and land temperatures. Even the slightest disturbance in a region of great temperature contrasts may set off a chain of events resulting in a cyclonic weather movement. Whatever the cause, the consequence is a wave-like undulation in the currents and the fronts that separate them. Sometimes the wave dies out, and a smooth flow is restored. More often, the currents meander back and forth in loops and swirls that ultimately develop into eddies several hundreds of miles across. At this point the cyclone spins off with a peculiar movement of its own.

Today the polar-front theory of the Bergen School seems highly oversimplified. Its air masses and fronts are useful and meaningful in the jargon of meteorologists, and are indispensable in weather maps and forecasts, but the theory itself is outmoded. The Bjerknes name today



A METEOROLOGICAL CHESS-BOARD was part of the dream plan for a numerical weather-forecasting centre conceived by Lewis Fry Richardson. He envisaged the world divided up into a chess-board of 2,000 observing stations, each supplying data. The map above is taken from his book. As Richardson saw it, shaded squares would report barometric pressure while light squares were sending in wind data. Names are points which Richardson knew to be at or near the centre of their squares; each square, even at sea, would have a station at its centre.

is associated more often with the polar-front theory than with the bold dream of an exact science of weather forecasting. And yet the dream was far more important—even if, despite his valiant efforts, Bjerknes himself did not make it come true. He had the right formulae, the right data and the right idea, but the mathematical technique needed to make the system work remained tantalizingly out of reach.

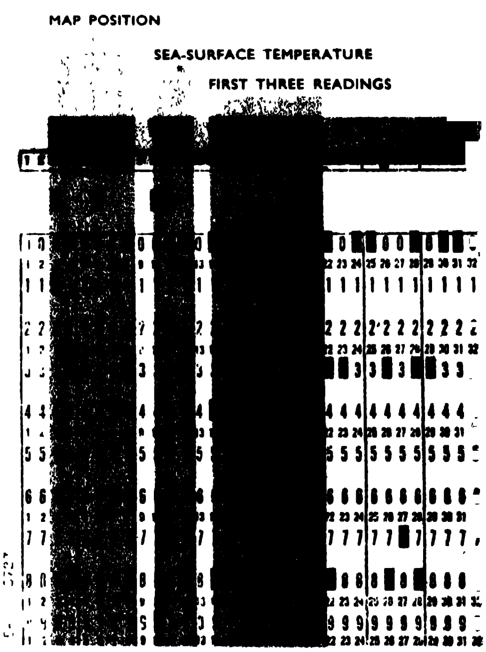
Even as the Norwegians struggled with their problem, however, a solution was taking shape in the mind of a British mathematician, Lewis Fry Richardson. Richardson thought it might be possible to solve the complex equations that eluded the Norwegians by working them out in step-by-step computations using simple addition, subtraction, multiplication and division. All through World War I, in between ambulance-driving duties, Richardson toiled away at his manuscript. Finally, in 1922, it was printed under the title *Weather Prediction by Numerical Process*. It was a strange and quixotic addition to the literature of science, proving that numerical methods do indeed solve the problem, but it had two drawbacks. To put it into practice, he needed data from upwards of 2,000 permanent weather stations around the globe, equipped to collect both surface and upper-air readings. And the numerical processing of this would have required an army of 64,000 mathematicians punching away at 64,000 calculators 24 hours a day, each day of the year.

Richardson must have realized that he was demanding a physical impossibility, for he went on to describe a "forecast factory" that at the time was pure science fiction. It would be a large circular hall, like a theatre-in-the-round. The walls would be painted to form a map of the globe, with the North Pole on the ceiling, England in the balcony, the tropics in the dress circle, and Antarctica in the orchestra pit. The 64,000 calculators would be clicking away, each in its assigned position, and electric signs would flash their answers.

An orchestra of weathermen

From a raised pulpit in the centre, the supervisor and his staff would control the whole operation. One of his duties would be to see that no part of the world fell behind in its calculations. "In this respect," wrote Richardson, "he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines." As fast as the predictions were computed, pneumatic tubes would whisk them to a remote room for coding and relaying to a radio transmitting station.

Incredibly, less than 25 years later it all began to come true. Speeded by World War II technology, the centuries-long evolution of the calculating machine finally produced a contraption that could do the work not of merely 64,000 mathematicians, but of 100,000. One of the first of these electronic computers was von Neumann's MANIAC.



A TICKET TO A FORECAST, the IBM card above is what enables a computer to turn weather data into a prediction. The grey horizontal band at the top starts at the left with a code (J 6) indicating where the data were collected. A second code (RP) indicates readings representing sea-surface temperature. The readings themselves follow. These data, punched on a series of four cards, tell the computer the sea temperature every 310 miles along a line stretching from the central Pacific to the north-east coast of Africa.

This machine seemed the perfect solution to the crushing mechanical difficulties so appealingly, and so hopelessly, presented by Richardson in his *Weather Prediction by Numerical Process.* Accordingly, in 1946, von Neumann began to assemble at Princeton a group of young, creative and highly talented meteorologists and mathematicians.

For the next 10 years, these and other top scientists in the field toiled at the trail-blazing task of reducing the intricacies of meteorology to a form that could be digested by a high-speed computer. They diagnosed the errors of Richardson's calculations, worked out formulations of existing equations, solved previously unassailable problems and analysed far more new data than Richardson could ever have dreamed of.

Von Neumann's scientists had at their disposal a vast network of weather stations, which were feeding in information from 100 million cubic miles of space, and modern weather balloons carrying the latest electronic sensing and transmitting equipment. By 1956, von Neumann's team had finally and firmly established the foundation for a new and far more sophisticated meteorology: the analysis and prediction of weather by mathematics and machine.

"Perhaps some day in the dim future", Richardson had written, "it will be possible to advance the computations faster than the weather advances." That "dim future" had arrived.

Myths, Deities and Computers

The study of weather began as myth. To early man, weather was a divinely ordered phenomenon, and tribal priests related storms and fair weather to the mood of the gods. In the fifth century B.C., Greek philosophers first began to suspect that there were natural causes behind the weather. But lacking instruments and an understanding of the laws of physics, they could only speculate. Slowly, however, the tools for measuring weather became available. At the same time, such brilliant scientists as Newton and Boyle were formulating the physical laws essential to the study of weather. It was not until the early 1900's, when meteorology finally came into its own, that the complexity of this new branch of science began to be realized. Today, meteorological computations are being handled by computers—which have demonstrated, among other things, that inherent in the subject are problems that will stump computers as yet undesigned.

A MEDIEVAL GUIDE TO THE WINDS
Man as microcosm is subject to the winds of the greater world in this medieval miniature. The fire, water, earth and air, of which man and universe were thought to be composed, are portrayed affecting the nature both of the winds and of man. Each wind has its own character. The east wind (*top*) is "drying" and "temperate", while the west wind (*bottom*) "dispels winter, produces flowers".

THE U.S. WEATHER BUREAU's National Meteorological Center (NMC) in Suitland, Maryland, the largest weather-computing centre in the world, is, in effect, the forecast factory that Lewis Fry Richardson dreamed of and that John von Neumann did so much to bring to fruition. Here, four times a day, an enormous complex of computers devours millions of bits of weather data from thousands of observing stations all over the Northern Hemisphere, hums through millions upon millions of calculations, and within 90 minutes or so starts flashing coded numerical weather analyses and forecasts by Teletype to hundreds of Weather Bureau and military offices throughout the United States and lands overseas.

At the NMC, not even the weather maps are drawn by human hand. Automatic curve-plotters integrated with the computers sketch out maps of weather and winds over the Northern Hemisphere as they were a few hours ago; throughout the far-flung network of recipient stations, the maps simultaneously appear as if by magic on electrolytic facsimile printers. Thanks to electronics, the NMC can send such a volume of information to each station that the weatherman on the spot can make a local prediction without so much as a glance out of the window.

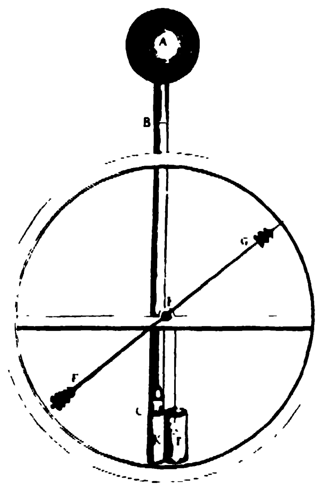
Still, not even an organization as big as the NMC is large enough for the meteorologist to reach his elusive goal: the perfect forecast every day of the year. Which way the weather will go depends on many factors; one expert has suggested only half-facetiously that the guesswork will not begin to be removed from prediction until there is a weather-reporting station for every two square inches of the earth's surface. Meanwhile, as the late English meteorologist and author, Sir Napier Shaw, once wrote, "A forecaster's heart knoweth its own bitterness, and a stranger meddleth not with its joy". The weather still flirts with the forecaster and makes a fool of him, but if he outguesses it he can congratulate himself on his own shrewdness and learning. And as he looks back to the past, he cannot help but take satisfaction in how far his professional art has come from where it started.

For many centuries men believed that weather changed at the whim of the gods. Bad weather, in fact, was one of the principal ways in which the gods toyed with man. Writing in about the eighth century B.C., Homer describes how Poseidon, god of the sea, seeing Odysseus adrift on his raft, "gathered the clouds and troubled the waters of the deep . . . and he roused all storms of all manner of winds, and shrouded in clouds the land and sea".

But even while the Greeks were attributing weather to the whims of the gods, they were also studying weather as a phenomenon subject to natural laws. By the fifth century B.C. they were publicly posting weather observations—wind data for the most part—for the use of mariners. In the fourth century B.C. Aristotle wrote his monumental study

A COMPUTER'S ROSE
This flower-like picture is actually an early type of numerical forecast predicting some of the next day's weather elements—such as pressure force and wind speed—for the Northern Hemisphere. Such forecasts are read by meteorologists like a map, with the centre representing the North Pole. The patterns are produced by the computer from hundreds of observations.

of the physics of the earth and air, *Meteorologica*. But weather prediction was still necessarily a matter of reading natural signs in advance. The most industrious compiler of this classical weather lore was Aristotle's pupil Theophrastus. His *Book of Signs*, written about 300 B.C., described more than 200 portents of rain, wind and fair weather, and a few that were alleged to reveal what the weather would be like for the coming year or more. He described signs to be found in the behaviour of sheep, the way a lamp burns during a storm and the crawling of centipedes towards a wall. His book was a major reference work for forecasting for the next 2,000 years.



A WHEEL BAROMETER, designed in 1666 to permit more accurate readings of the changes in a standard tube of mercury, was invented by Robert Hooke, one of the most ingenious mechanical innovators of his age. A small float, riding on the column of mercury, was connected by a string to a pulley which moved a pointer, thus making it possible to observe relatively minute changes in barometric pressure.

The myth of the flies

Many of the curiosities that still linger in popular weather lore can be traced right back to Theophrastus—for example, the myth that flies bite excessively before a storm. In fact, flies bite equally hard and often in any weather. On the other hand, some of Theophrastus's observations have been made many times, under many skies, and have remained current for good reason. Theophrastus noted that a red sunrise and a halo around the sun or moon are all portents of rain, while a red sunset is a portent of good weather. All have been shown by one modern meteorological study to be accurate at least 7 times out of 10.

But on the whole, ancient weather wisdom was a sketchy and highly subjective guide for forecasting. The scientific study of weather had to wait until the 17th century and the development of instruments for quantitative measurements. In the 25 centuries since the time of ancient Greece, men had commonly used tools to measure only two elements of weather: rainfall and wind direction. They used a bucket and ruler to find the first, and weather vanes to find the second. When more instruments finally came, they came swiftly, sweeping away within the century the dominion of Aristotle, Theophrastus and old shepherds' tales.

First to be used for prediction was the barometer, invented by Torricelli in 1643. Renaissance scientists were soon fascinated to observe that certain kinds of weather often accompanied certain pressure readings. The barometer came to be called the "weather glass", and was believed for a time to be a foolproof weather prophet. When Robert Hooke devised a wheel barometer, with a pointer and dial to indicate the rise and fall of the mercury, predictions were made part of the barometer itself—and can still be seen on some barometers: "Change" at 29.5 inches of

A barometer's chief usefulness to forecasting today is to indicate that change itself is on the way, for a change in pressure does indeed usually herald a change in weather. But exactly what *kind* of weather will arrive can be foretold only with much more information than the barometer alone supplies.

Along with the barometer came the thermometer and Robert Hooke's "hygroscope" for measuring humidity. Armed with these instruments, the enthusiastic scientists of the 17th century began laying the basis for a real understanding of weather: the keeping of careful records. Scientific observation had to precede scientific prediction. Over the next 200 years, the first modern meteorologists built up a storehouse of recorded measurements, not only in order to learn more about the physics of weather, but also to discover its movement and patterns, so that predictions might be made on the basis of the past.

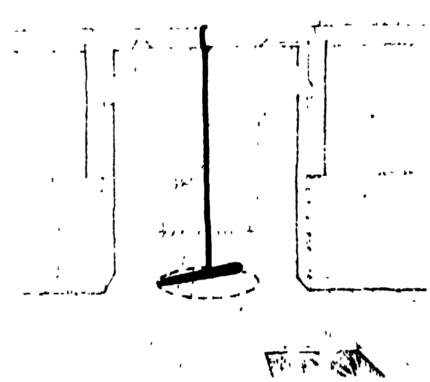
Records still exist of simultaneous observations made between 1649 and 1651 in two French cities—Paris and Clermont-Ferrand—and in Stockholm, Sweden. The records, delivered by a primitive postal service, arrived at the collection point days or weeks behind the atmospheric conditions they described. By the end of the century, regular records, both local and international, were being kept by such diverse parties as Central European grand dukes, England's Royal Society, and the city of Charleston, South Carolina. Information passed from scientist to scientist, and from country to country, giving meteorology the co-operative, international character that distinguishes it to this day.

A statesman-like interest in weather

Many of the great men of the 18th century interested themselves in weather just as they interested themselves in other momentous affairs of the time. Benjamin Franklin's contribution to meteorology was conspicuous, but George Washington, Thomas Jefferson, James Madison and John Quincy Adams all kept weather records. (In Philadelphia on the morning of the 4th July 1776, the day the Declaration of Independence was adopted, Jefferson recorded the temperature at 6 a.m. at 20° C.) Boston's weather records were kept jointly by a Harvard professor and the Chief Justice of Massachusetts.

Eventually, weather records were being kept throughout the civilized world. In the early 1800's, U.S. Army hospital surgeons were ordered to take regular observations—thus beginning the first meteorological service financed by the U.S. Government. By 1853 weather records were being filed daily in 97 different Army camps.

As data became more abundant, instruments more accurate and observational techniques more uniform, students of weather gained an ever-clearer picture of its passage over large areas. By the 19th century,



A HAY-LOFT HYGROMETER, made of rope and a stick, is a home-made instrument for forecasting bad weather. When the air's humidity increases, the rope absorbs moisture. Its strands lengthen and unwind slightly, moving the stick in a circle. When the humidity drops, the rope winds up again, reversing the stick. Crude but fairly accurate, this rustic instrument was based on an old farmers' saying: "When the ropes twist, forget your haying".

meteorologists had ample confirmation of one of the central precepts of forecasting: that weather develops progressively as the atmosphere flows across the face of the land. Weather maps drawn in the 1840's by James Espy and Yale University's Elias Loomis established the generally west-to-east progress of cyclonic storms. But this knowledge of weather's broad movements was of no practical use as long as weather news could be sent no faster than stage-coach or ship could carry it. The charts that the theorists patiently constructed showed weather long since past, weather that had already lost its significance for the present, let alone the future.

A miracle of communication

Samuel F. B. Morse's electromagnetic telegraph finally wrought the miracle of rapid communication—and revolutionized meteorology as dramatically as had the thermometer and barometer some 200 years before. The first telegraph lines were built between Washington, D.C. and Baltimore in 1844. The implications for meteorology were immediately grasped by Joseph Henry, an inventor of an earlier telegraphic device himself, and now secretary of the recently founded Smithsonian Institution in Washington. In 1849—almost as fast as telegraph wires were going up—Henry began making a series of agreements with telegraph companies whereby the Smithsonian provided meteorological instruments, and operators telegraphed weather data to the Smithsonian in return.

By the end of the year, operators in dozens of stations were under orders to give weather data top priority, and opened shop each morning by tapping out coded pressure and temperature readings and other weather information. Soon the Smithsonian was publishing daily weather maps of the area encompassed by the network—among the first based on telegraphed data. They were not forecasts, but astute interpreters knew that a storm located over Cincinnati on today's map might well hit Washington tomorrow. By 1860 and the outbreak of the Civil War, upwards of 500 telegraph stations were making the wires hum with national weather information for Professor Henry.

Other nations were as quick to exploit the telegraph, and were even quicker to move from collecting current data to forecasting. The French were the first to establish a national storm-warning service, begun in 1856 after the disastrous loss of French and British naval vessels in the Crimean harbour of Balaclava in a storm (*page 146*). The British launched a similar service in 1860, after a steam clipper was wrecked on the coast of Wales in a gale, with a loss of 450 lives. American progress towards forecasting, however, was seriously interrupted by the Civil War. The war broke the links of Henry's chain of telegraph stations serving the

Smithsonian, and he was never able to re-establish it on such a large scale again.

Organized weather forecasting in the United States was begun not in Washington but in the Mid-West, and not by the government but by one man, the director of the Cincinnati Observatory, Cleveland Abbe. Abbe persuaded both the Cincinnati Chamber of Commerce and the Western Union Telegraph Company of the practicality of local predictions, and with their backing began issuing regular forecasts, which he called "probabilities", on the 1st September 1869. He said prophetically at the time, "I have started that which the country will not willingly let die". He received bulletins from only two telegraph operators that first day, but he issued his probability nevertheless predicting easterly and south-easterly winds. By the end of the year he had a small network of 33 observers telegraphing information.

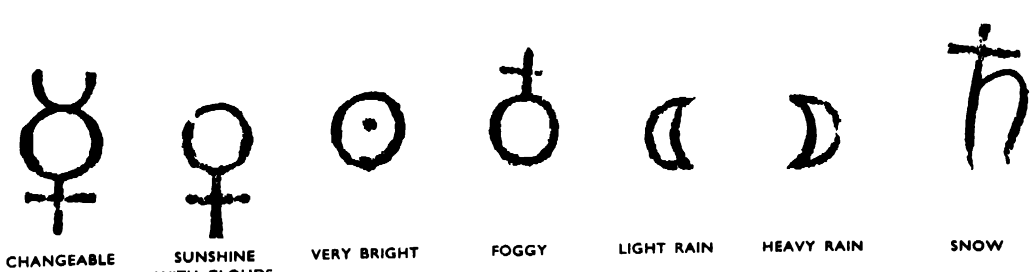
The next year, in response to mounting pressure from Great Lakes shippers for storm sarnings, the U.S. Congress at last appropriated money for a government-sponsored forecasting agency, placing it under the control of the U.S. Army Signal Service. Its first forecast was issued on the 8th November 1870, by Increase Lapham, a Wisconsin scientist. It was based on telegraphic reports from 25 stations, most of them in the Mid-West, and was distributed in the Great Lakes area. The forecast read, "High winds probably along the Lakes".

From this beginning, with its pitifully inadequate network of 25 primitively equipped stations, 233 full-time employees and an annual budget of £17,000, has grown what may well be the most complicated and far-flung peacetime organization in history. The modern United States Weather Bureau, operating within the Environmental Science Services Administration (ESSA) of the Department of Commerce, now has under its jurisdiction approximately 300 surface weather observation stations, some 145 upper-air sounding stations on land and at sea and nearly 100 radar weather surveillance stations. Its number of full-time employees has multiplied more than 20 times to nearly 5,000, and its annual appropriation is somewhat over £30 million. As one measure of the usefulness of its work, every year Americans make approximately 250 million telephone calls to get tape-recorded forecasts of tomorrow's weather.

A formidable mosaic

The task of the Weather Bureau is staggering to contemplate. In brief, it is to observe and analyse more than 2,000 million cubic miles of atmosphere that envelops the Northern Hemisphere in a shifting mosaic of weather—a mosaic so complex that the Bureau once estimated that the U.S. alone may be covered by 10,000 varieties of weather at once, each significant enough to be of local concern.

CABALISTIC SIGNS, similar to those devised by medieval astronomers, were borrowed in the 18th century by the Swiss-German scientist Johann Heinrich Lambert, who used them in a weather book published in 1758. Signs such as these came into widespread use in the 18th century as methods of gathering and exchanging weather observations were increasingly refined by individual scientists and learned societies. They were the precursors of modern meteorological symbols.



The national, international, public and private resources used by the Bureau to accomplish its task are almost equally awesome. Throughout the Nothern Hemisphere, some 2,000 stations of many nations regularly transmit weather data to national or regional collecting centres four times a day, seven days a week. About 500 of them are in the area of most immediate concern to the U.S.: the continent of North America and the surrounding seas. Another 1,500 are land-based stations around the world: stations in Red China, Siberia, the Sahara; in the mists of the Scottish highlands, or in the tropical warmth of Hawaii. Such is the international etiquette of weather-collecting that in all these places the weathermen on duty perform much the same daily ritual. At midnight, 6 a.m., noon and 6 p.m. Greenwich time, they emerge like the shepherds of old, look at the clouds and note whether the air is hazy. Being modern weathermen, they also read their barometers, thermometers, rain and wind gauges and hygrometers. By radio they transmit the data thus obtained to their headquarters. Perhaps half a world away, the receivers at the NMC pick up the vast body of information, teletypewriters code it on tape and get it ready for the computers' next meal.

Weather reports from sea and sky

On an average day the NMC also picks up some 3,200 ship reports on weather throughout the seven seas, nearly 1,000 reports from commercial aircraft in flight, and at least 200 reports from scheduled reconnaissance flights by military aircraft.

In addition, more than 500 stations in the Northern Hemisphere report on the direction and speed of the great rivers of wind streaming through the stratosphere and troposphere. Twice a day, and sometimes four times a day, radiosonde balloons are sent into the skies over 100 North American stations. They climb at 1,000 feet a minute, their delicate sensors reading temperature, pressure and humidity as they soar upwards, their tiny radios flashing the data earthwards, until the balloons burst at altitudes of 60,000 or 70,000 feet. All these data, too, converge on the teletypewriter banks at the NMC, and are fed into a battery of computers.

According to a recent publication of the Bureau, one purpose of this vast human and technical endeavour is "to determine and record the . . . climatology on the North American continent and adjacent waters". Another is the discovery of "natural laws governing atmosphere phenomena". But the Weather Bureau's first and foremost function is to forecast weather to tell a waiting public what kind of day it will be tomorrow and the day after.

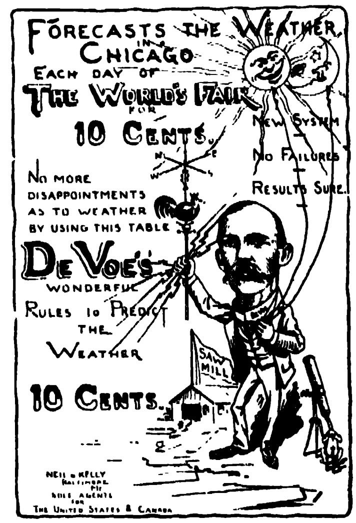
Each year the U.S. Weather Bureau turns out about 1.2 million general weather forecasts and 750,000 aviation forecasts. It issues 100,000

river-stage and flood forecasts, and additional thousands of special warnings and bulletins regarding tornadoes, hurricanes, hail, lightning, high winds, blizzards, cold waves, fog and frost. Its services are probably used every day by more people than those of any other single government agency except the U.S. Post Office.

The Bureau's short-range forecasts covering the next 18 to 36 hours, issued locally four times a day across the country, influence the life of the nation in all its phases. The property dealer with a model home to show on Sunday, the bride who wants an out-door reception, the garage-man ordering his antifreeze supply, all these and millions more are vitally interested in tomorrow's weather. They listen with various degrees of feeling to what their local Weather Bureau forecaster has to say about it. One housewife living near the Connecticut shore regularly checks her local station for cloud-cover and ceiling-height forecasts before stating her laundry. She explained to a puzzled weatherman, "When the ceiling is low, the sea gulls fly right over my backyard, and it's no time to hang out laundry. When the ceiling is high they fly another route".

The money the American public saves through this glimpse of the weather ahead is incalculable. The glib estimate is £400 million a year, but responsible meteorologists place it much higher, and not only in terms of money. Current Weather Bureau figures, for example, indicate that its storm warnings alone not only prevent some £100 million in property damage each year, but also save some 2,600 lives.

Jokes about the Weather Bureau's inaccuracy are, roughly, a generation out of date. There is disagreement over how the accuracy of a prediction is measured, but according to Weather Bureau calculations, accuracy reached a relatively high point in the 1940's, when World War II led to an intensification of effort and new techniques. The percentage of accurate forecasts then levelled off for roughly the next 10 years. Figures varied slightly for different sections of the country, but during this period Bureau forecasts for 12 to 18 hours in advance were about 80 per cent accurate in most areas. Forecasts for 24 to 36 hours in advance were about 70 per cent accurate.



WEATHER WIZARDRY, published for the Chicago World's Fair in 1893, forecasts the weather for all 183 days of the exposition. Its bold author based his "rules" on the notion that weather remains stationary while the earth moves under it, according to a predetermined pattern. Thus, he believed that Chicago would have the same weather in June that had occurred at the equator the previous December.

A boost from computers

When the U.S. Weather Bureau first began using computer technology in 1955, an improvement in accuracy, "slight but significant", was noted almost immediately. Today 12- to 18-hour forecasts are considered 85 per cent accurate; forecasts up to 36 hours in advance are correct about 75 per cent of the time. Though general weather conditions for about a week in advance can be forecast with some degree of usefulness, it is still beyond the capabilities of science to make detailed predictions for more than about three days in advance.

The achievement of more accurate forecasts, particularly for relatively extended periods, would be of incalculable value to everyone. President Johnson has estimated that if weather could be accurately predicted only five days in advance, government and industry in America alone would save an additional £2,000 million annually in better water-resources management, and lower costs in agriculture, surface transportation, retail marketing and lumbering.

With such an enormous commercial incentive, accuracy can and will improve. Better reporting of weather over vacant land areas and oceans is now a major objective of the U.N.'s 126-member World Meteorological Organization. Scientists the world over are seeking a better understanding of the atmosphere, improved techniques for handling masses of statistics, more elaborate computers. All these lines of inquiry will help to make tomorrow's weather more predictable.

Such is the pace of technology that it is not hard to imagine a day when every weather prediction is as accurate as it needs to be for the most efficient human planning. Yet even in such a brave new world, weather will still have its unique charm. It is one thing to hear temperature, pressure and humidity predicted with utmost precision over the radio, and another to step outside and find them there. A fine day is always a happy surprise.

The Home Weatherman

Meteorology is among the most complex of the physical sciences. In its effort to predict what tomorrow's weather will be, the U.S. Weather Bureau employs some 5,000 people, has an annual budget in excess of £30,000,000, utilizes one of the most complicated computers ever built and has access to the weather data collected by more than 100 nations. Yet many Americans are discovering that they can do remarkably well at predicting the weather using only a few pounds' worth of equipment. These parlour meteorologists are often surprisingly youthful. John Sims (*opposite*) was only 13 when he built his own weather station, entered it in a national science contest and won a prize. His forecasting score was far from perfect, but the judges took into account the special handicaps that only an amateur weatherman must cope with—such as the fact that when a west wind blows, John's wind readings are affected by a neighbour's hedge.

A DO-IT-YOURSELF METEOROLOGIST
Entering observations on a weather chart, John Sims stands beside his back-garden weather station in Flushing, New York. The station's equipment includes (*from left*) an anemometer for measuring wind speed, a wind-direction indicator, and a shelter housing instruments for recording temperature and humidity. Except for thermometers, all were built from material available at home.

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